OF ROAD TUNNELS

TION

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VENTILATION OF ROAD TUNNELS

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ROYAL INSTITUTE OF ENGINEERS (KIVI) DEPARTMENT OF TUNNEL TECHNOLOGY AND UNDERGROUND ENGINEERING WORKS WORKING PARTY "VENTILATION OF ROAD TUNNELS"

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SUMMARY (L. Swart)

These new recommendations are of interest because they are based on four important subjects, namely: "emission", "vehicle distribution and density", "fire" and "calculation method". All the other subjects reported have been adjusted as far as possible to the most recent data but are not so very directive.

The reason why the subject of "emission" is a new one is that other substances have been added besides carbon monoxide. In addition a method to determine vehicle distribution is outlined in the first chapter of these recommendations and in the subsequent one on vehicle density. The determination of vehicle distribution does not only imply that information is required about emission for each vehicle but also information about the type and number of vehicles on the road. The most recent research information obtained from research in this field is reported for both these subjects.

The subject "fire" in a road tunnel is completely new in these recommendations and provides important information concerning the safety of the public and the tunnel systems in the event of a fire in the tunnel. The reason for giving extensive attention to this subject this time is prompted by the current development in the Netherlands of opening tunnels to the transport of dangerous substances. Until recently this type of transport was not permitted through road tunnels in the Netherlands. Finally there is a great need for a better calculation method to determine the capacity of the ventilation system. Developments in the direction of probabilistic calculations have made it possible to apply these methods to the calculations of ventilation in tunnels. In principle this method differs from the prevailing deterministic method in that account is taken of a permissible probability of failure while the deterministic method tries to prevent dangerous situations from arising by using safety margins.

At the time that these recommendations were made the working party was composed as follows:

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CONVERSION FACTORS (R.C. Rijkeboer)

In these recommendations emission is measured in g/h. The conversion to l/min and the reverse are as follows:

compound		1/m	in → g/h	g/ł	i → l/min
carbon monoxide	(co)	1	75	1	0,0133
benzene	(C6H6)	1	209	1	0,00478
nitrogen dioxide	(NO2)	1	123	1	0,00813
benzapyrene	(BaP)	1	675	1	0,00148
sulphur dioxide	(SO2)	1	176	1	0,00569
ozone	(03)	1	128	1	0,00788

For the conversion of 1/km to g/h and the reverse the following factors apply:

compound	1/4	km → g/km	g/k	m → 1/km
carbon monoxide (CO)	1	1,25	1	0,800
benzene (C6H6)	1	3,50	1	0,287
nitrogen dioxide (NO2)	1	2,05	1	0,488
benzapyrene (BaP)	1	11,3	1	0,0888
sulphur dioxide (SO2)	1	2,93	1	0,341
ozone (03)	1	2,14	1	0,467

For the conversion of g/km to g/h and the reverse it applies that:

$g/h = g/km \ x \ km/h$

The conversion of ppm to mg/m^3 and the reverse are as follows:

compound	ppm	→ mg/m3	mg/m3 → ppm		
carbon monoxide	(co)	1	1,16	1	0,850
benzene	(C6H6)	1	3,25	1	0,308
nitrogen dioxide	(NO2)	1	1,91	1	0,524
benzapyrene	(BaP)	1	10,5	1	0,095
sulphur dioxide	(SO2)	1	2,73	1	0,367
ozone	(03)	1	1,99	1	0,501

1 INTRODUCTION (L. Swart)

1.1. OBJECTIVES

The objectives of these new recommendations can be formulated as follows:

Documentation of knowledge

There is a considerable amount of knowledge in the field of tunnel ventilation available in the Netherlands. This knowledge is, however, known by individuals and will be lost after some time if it is not passed on. By documenting the current state of knowledge expensive mistakes will be avoided being made again in the future. The current experts in this field have acquired their knowledge by trial and error. It would be particularly unfortunate if future designers make the same mistakes again.

Anticipating the current state of affairs

Due to the increasing pressure of traffic and increasingly more stringent environmental requirements there are not only plans to build a large number of tunnels in the future but also to build lowered roads which will be totally or partially covered over. This does not only apply to the national government but to local governments as well. These recommendations ensure that the designers at all the government bodies involved in these projects will make a ventilation design which is technically as well as an economically sound.

Boundary conditions and basic assumptions

Several different fields of study are involved in the design of a tunnel ventilation system, thus making it necessary to bring these disciplines together before the boundary conditions and basic assumptions, which the design must meet, can be specified. By using these recommendations a considerable saving can be made at this predesign stage.

Cost reduction

As with all standardization work, savings can be expected if these recommendations are accepted by the commissioning authorities, designers and industry. To facilitate acceptance of these recommendations the working party is composed of volunteers from industry, research institutes, engineering consultancies and government departments.

Determining the capacity of ventilation systems

To make tunnel designs which are as economic as possible one needs to be able to determine the capacity of the ventilation system in a well-considered way. The probabilistic calculation method ensures that this requirement is met without having the result of introducing an unacceptable safety risk.

Standardization of measuring methods

In order to be able to compare different ventilation systems with each other, the measuring method for the guarantee measurements must be standardized in the laboratory as well as in the tunnel. In addition this also facilitates the comparison of booster products with each other.

1.2. FORMULATION OF THE PROBLEM

As mentioned in the preface different considerations are involved when bringing out new recommendations. One of the reasons is that the current formulation of the problem is more detailed than in 1975. The most important points are described in the following.

Fire (see Chapter 2)

The design scenarios have been adapted to current insights and calculation methods in which attention is especially paid to "fire". It appears that fires in closed underground areas frequently take a heavy toll of casualties due to suffocation. A tunnel is no different in this respect but in addition due to allowing the transport of dangerous substances the risk of enclosed fires is considerably greater than in previous years when this transport was not permitted through tunnels. The problems which have arisen as a result of this are high temperatures and the poisonous combustion gases.

Traffic (see Chapters 3 and 4)

The application on a large scale of improved combustion engines, catalytic converters and the increased use of diesel engines has resulted in a drastic decrease in the discharge of dangerous substances. In addition to taking into account the sharp reduction in exhaust fumes, the emission of nitrogen dioxide (NO₂) and benzene (C₆H₆) as well as particles (soot) are determined by a calculation model. Attention is being paid to the emission of several dangerous substances, although the probabilistic calculation for this is not ready yet. Research is also being carried out in the field of the composition and density of traffic for a larger number of categories of vehicles.

Ventilation systems (see Chapter 5)

In addition to looking at classical ventilation systems, attention is also paid to longitudinal ventilation in particular because this system is the one most applied in the Netherlands. The latest development in this area is also discussed, namely a combination of an open injector and boosters distributed along the whole length of the tunnel. This method meets the requirements the best in the event of fire in a tunnel.

Environment (see Chapter 6)

Environmental policy has changed a great deal since 1975. The requirements now being set with respect to the environment cannot be ignored any more. Attention has therefore been paid to the current and expected requirements with respect to the environment. Attention is paid to the permissible concentrations of air pollution inside as well as outside the tunnel. In general it can be stated that compared to 1975 the requirements are new or have been considerably highlighted.

Calculation method (see Chapters 7-10)

The probabilistic calculation method is extremely suitable to designing ventilation systems which can be applied in practice. The deterministic method, which has been used up to now for the ventilation calculations, gives results which bears no relation to the probability of occurrence. The most important difference between the two methods is the attribution of a probability distribution to the stochastic functions. In the new recommendations a deterministic calculation method worked out manually is given in graphical form and only the probabilistic method is used for further calculations.

Although in Chapter 5 attention is paid to different ventilation systems, only information from longitudinal ventilation by means of boosters is used in the probabilistic calculation method. This system is the most suitable one for the normally short tunnels in the Netherlands.

The application of the probabilistic calculation method to longitudinal ventilation by means of boosters takes a great deal of time. The method has as a result only been partially completed. However, sufficient insight has been gained into two representative situations, namely the "large fire" and "emergency assistance" scenarios. It was decided to work out these two situations as much as possible within the time available. The "large fire" scenario is the furthest developed and reasonably complete. For the other scenarios only the Hb-CO content of the blood has up to now been considered as an normative substance. To all appearances this is not a problem since carbon monoxide (CO) is still a determinative factor. This can, however, change in the near future due to the continual reduction in CO emission as a result of the use of catalytic conversion techniques and to the lowering of the permissible amounts of the other substances in the exhaust fumes.

In spite of the above-mentioned restrictions it was decided, albeit in this unfinished form, to present the method because of the experience gained with this calculation methodology.

Calculation examples (see Chapter 11)

Since the new calculation method must still be adopted, considerable attention has been given to several calculation examples. The calculations worked out manually as well as the calculations made by the computer program are discussed. The effect of wind in particular appeared to have a decisive effect on the determination of the capacity of the ventilation system.

Noise (see Chapters 12 and 14)

Information about noise pollution, inside and outside the tunnel, has been added to the recommendations because more attention is being given to this aspect at the present time.

Guarantee measurements (see Chapter 12)

This is a subject about which there are many differences of opinion. In order to put an end to these differences, it was decided to prevent further discussions about this subject by making unambiguous recommendations. By making references in the specifications for ventilation systems to the parts concerned in these recommendations, the commissioning authority is guaranteed that he will get what he has commissioned and for which he has paid.

Measurement and control systems (see Chapter 13) The recommendations pay attention to measurement and control systems. There is a great need for this in the practical situation, even the best systems do not operate if the control system fails.

Environment, safety and management (see Chapters 2, 6 and 14)

From the management standpoint more information is available about what should be done in the event of fire or other situations in which dangerous substances are involved. In this way the manager of a tunnel is capable of making the right decisions where the operation of the ventilation system is concerned.

Safety is closely associated with management, indeed many potentially dangerous situations can be avoided by correctly managing the situation. From this view point information is also available concerning the control procedures to be followed. Besides the consequences for safety, management of the tunnel also has an effect on the environment in and around the tunnel. Therefore several practical aspects are gone into in Chapter 14. The permissible concentrations of dangerous substances in the management of the tunnel are referred to in Chapter 6. This section on management only provides very global information at the moment and must be extended in the future.

2 DESIGN SCENARIOS (L. Swart)

2.1. GENERAL

In the design of a tunnel ventilation system agreement should be reached about the criteria which the system must meet. First of all the type of ventilation system must be determined to which the design scenarios apply. The starting point is *longitudinal ventilation by means of boosters*. This system has various alternatives, which are discussed in Chapter 5 but the scenarios given below apply to all these alternatives.

Design scenario means the different operating situations which are chosen as the basis for the calculation of the ventilation system. Many scenarios are possible but they are not all important as design criteria for the ventilation system. Therefore the description of 4 design scenarios will be sufficient here, namely: "stagnating traffic", "emergency assistance", "escaping motorist" and the most important "fire".

2.2. STAGNATING TRAFFIC

2.2.1 General

Stagnating traffic is a fairly frequently occurring situation in densely populated areas, such as the west of the Netherlands. Traffic-jam traffic is another term which is applicable here. The term "stagnating traffic" is used in these recommendations because it fits in better with the accepted international terminology.

The following basic assumptions are being used at present: stagnating traffic is taken to mean traffic moving forward steadily with a tailback through a tunnel. In addition it is assumed that the tailback is of a closed nature, thus no open spaces, in which the average speed in 95% of the cases is higher than 6 km/h. A tunnel 1,000 m long will take 10 minutes to travel through. The activity of the motorist is assumed to be "resting".

Since the effect of dangerous substances, such as nitrogen dioxide (NO_2) and benzene (C_6H_6) is only noticeable after prolonged exposure, no account has been taken of these substances during the time spent in the tunnel. In the "stagnating traffic" scenario two dangerous effects are taken into account, namely the absorption of carbon monoxide (CO) in the blood and the deterioration in visibility. Both effects must be acceptable. The acceptable volume of carbon monoxide bound to haemoglobin (Hb-CO) in the blood is determined by medical criteria. The permissible de-

terioration in visibility is mainly a safety/comfort aspect.

2.2.2. Absorption of carbon monoxide (CO) in the blood

The absorption of CO in the blood depends on the concentration, the length of time and the activity during exposure. Or that there is a connection between the consumption of oxygen by the body and the absorption of CO in the blood. May has studied these connections and recorded them in graphs. See appendix A. An increasing percentage of Hb-CO in the blood causes problems to the physical condition and health of the person. The consequences of this are noticed quickly, hence the high toxicity of CO.

It is known from research that with a percentage of 10% Hb-CO in the blood headaches arise in "normally" healthy people.

Another facet that is important concerns the starting condition of the people who use the tunnel. If as the result of smoking tobacco a certain percentage of Hb– CO is already in the blood then the permissible limit is reached earlier. Percentages of several per cent are easily obtained by a heavy smoker, so that the permissible limit chosen certainly should not be too high, if the category smokers is to be taken into account.

The medical condition of the person is yet another point which must be taken into account in the determination of the permissible Hb-CO limit. It is known that people with heart complaints experience problems earlier than other people on being exposed to CO. Heart patients get chest pains at CO percentages higher than 5%. From the health risk in the "stagnating traffic" scenario a limit of 5% Hb-CO in the blood is being maintained.

The last point which requires attention is the number of times a person is exposed to CO. A higher frequency is more dangerous than a single exposure. Therefore in the determination of the permissible limit for CO in the tunnel air an exposure of twice a day is assumed. People who use the tunnel more times a day, will therefore run a greater health risk than people who use the tunnel now and then.

2.2.3. Deterioration in visibility

Deterioration in visibility is understood to mean the decrease in transparency of the light in the tunnel air because of particles of dirt and soot in the tunnel air, with the result that the light is absorbed or reflected. If the air in the tunnel is 100% transparent, visibility is optimal. The transparency of tunnel air is measured by

an optical system which measures the decrease in the intensity of a beam of light over a measured distance. No decrease in the intensity of the beam of light is recorded as 100% transparent, if the intensity of the beam of light is totally blocked, transparency is 0%. The transparency is given as a k-value, with unit distance m^{-1} .

Visibility decreases as the transparency of the tunnel air decreases and also depends on the available light level. Visibility is important with respect to traffic safety. Light transmittance is especially important in connection with visibility in tunnels with low light levels. This situation is frequently found in mountain tunnels longer than 2 km. The light levels employed in the Netherlands are not so low that the transparency of the tunnel air quickly causes problems for visibility.

Another point which must be taken into account with light transparency is the percentage of goods vehicles which normally use the tunnel. It is conceivable that with large numbers of goods vehicles an unpleasant situation could arise as a result of odour pollution from the diesel exhaust fumes. Although there are no visibility problems in Dutch tunnels because of lighting levels employed in the central zone of the tunnel, odour pollution could be a reason to make stipulations concerning the transparency of the tunnel air.

Because odour is not quantitatively measurable, there is no sense in setting limits for this. There appears, however, to be a connection between the transparency of the air and the level of the odour pollution. It appears that as light transmittance decreases, odour pollution increases. By setting a permissible level for light transmittance the odour problem can be prevented.

At k-values of more than 0.004 m^{-1} , it becomes unpleasant to stay in the tunnel. Therefore this value is used as a maximum level for permissible deterioration in visibility, even though exceeding this level is not terribly critical.

2.3 EMERGENCY ASSISTANCE

2.3.1 General

As the result of a technical fault, lack of fuel, a punctured tyre, a small collision and such like, a traffic jam can build up on one or more traffic lanes which requires assistance. Emergency assistance in a tunnel is more difficult than in the open air due to the restricted space, ventilation current, noise and for some people the problem of claustrophobia. It is therefore important that the most favourable atmosphere possible is created during the traffic jam.

The ventilation system can contribute to this by operating at lower permitted levels during the traffic jam. Depending on the traffic load the ventilation capacity is increased. A second way of creating the best conditions as possible for a stay in the tunnel is to increase the lighting level which has a good effect on people especially those suffering from claustrophobia.

Because the effect of dangerous substances, such as nitrogen dioxide (NO_2) and benzene (C_6H_6) is only noticeable after a long exposure, these substances are not taken into account during the stay in the tunnel. Two dangerous effects are considered in the "assistance" scenario, namely the absorption of carbon monoxide (CO) in the blood and the deterioration in visibility. Both effects must be limited. The permissible volume of carbon dioxide bound to haemoglobin (Hb-CO) in the blood is determined by medical criteria. The permissible deterioration in visibility is mainly a safety/comfort aspect.

2.3.2 Number of traffic lanes

The number of traffic lanes in tunnels varies for each tunnel tube from 1 to 4. In most instances when several traffic lanes are blocked, the control room will close the whole tunnel tube to traffic. In tunnel tubes with more than 2 traffic lanes the traffic jam can be confined to one traffic lane which is not adjacent to the left or right wall. The control room will usually decide to block off the adjacent traffic lane as well. The traffic is then able to pass by on the left of right of the traffic jam. If the blocked lane is adjacent to the wall, then only this traffic lane is closed to traffic by using traffic lane indicators.

The basic assumption in the "emergency assistance" scenario is that the traffic held up in the remaining traffic lanes will travel at a reduced speed of an average of 25 km/h. Thus in a 2-lane tunnel tube 1 lane remains in use and in a 3 or 4-lane tunnel tube 2 or 3 traffic lanes remain in use, respectively with an average speed of 25 km/h.

2.3.3 Members of the emergency services

Assisting personnel are understood to mean the personnel from the breakdown and towing service, the police, the fire brigade, the medical service and the roadmen of the Directorate-General of Public Works and Water Management. It is assumed that "normal" healthy people are involved. But as already noted in the section stagnating traffic (2.2), the determination of the permissible limits of dangerous substances must take account of the category smokers.

2.3.4 Absorption of CO in the blood

To be able to give assistance in the event of small accidents and traffic jams referred to in the "emergency assistance" scenario, the assisting personnel will "work" for a maximum of 1 hour. It is assumed here that the absorption of CO in the blood goes according to May's curve. This absorption depends on the effort which must be made, or is associated with the oxygen consumption of the human body. That is why it is assumed that the assisting personnel "work" for this hour. If more time is required to solve the problems, then the tunnel tube must be totally closed in order to be able to give safe emergency assistance.

The member of the emergency services will carry out work regularly in the tunnel and therefore runs a higher health risk in the event of exposure to too high a concentration of dangerous substances. Besides which the assisting person is also a motorist and will also use the tunnel to get to and from work. In addition the category smokers in the assisting personnel must also be taken into account.

Due to the above-mentioned reasons it is clear that a lower chance of exceeding the permissible level must be taken. Or in other words: the chance that a member of the emergency services is exposed to a higher concentration than 5% Hb-CO must not be greater than for a motorist who uses the tunnel every day. The larger number of times a member of the emergency services stays in the tunnel is taken into account in the determination of the permissible chance of exceeding the limit. See Chapter 9 section 9.4 for further information.

2.3.5 **Deterioration in visibility**

With respect to the safety of the emergency services and the traffic it is essential that visibility conditions are good. The permissible deterioration in visibility is the same as the value for stagnating traffic.

In addition attention must be paid to comfort. Due to the fact that working in an atmosphere, in which there is a high concentration of diesel exhaust fumes, can be extremely unpleasant and/or damaging to health, the permissible k-value for the transparency of the tunnel air is at least halved with respect to the value for stagnating traffic.

From the safety point of view a higher permissible kvalue can therefore be used but due to the reasons of comfort mentioned above the lower k-value is employed in the "emergency assistance" scenario.

2.4. ESCAPING MOTORIST

2.4.1 General

The basic assumption for the "escaping motorist" scenario is a total obstruction of the tunnel tube due to an accident without fire. The traffic comes to a complete standstill and will fill the tunnel tube from the site of the disaster after a long or short time.

2.4.2 Escape corridor

An escape corridor is present between the two tunnel tubes in most modern tunnels which have been opened to the transport of dangerous substances. Since this provision is not, however, always present and in addition it is not always certain to what extent the public makes use of this provision, it was decided to opt for an unambiguous description of the "escaping motorist" scenario by assuming that the motorist does *not* make use of the possibly present escape corridor.

2.4.3 Direction of escape and delay period

Escape in the direction of the scene of the disaster is considered to be impossible, so that the motorists must leave the tunnel on foot in the direction of the tunnel entrance. The control room gives instructions via a loudspeaker system to turn off the engine and leave the tunnel on foot. To make these instructions understandable, the noise from the ventilators must not be higher than 100 dB(A) (see Chapters 12 and 14 for more information). It is uncertain to what extent the public follows instructions given via the loudspeaker system. It is assumed that in the event of prolonged blockages there will be a delay before people leave the tunnel. It is reasonable to assume that people still expect to be able to drive on. A delay period is thus logical and is arbitrarily set at 10 minutes.

The instructions given via the loudspeaker system instruct the motorist to turn off the engine. It can certainly be expected that in the delay period only some motorists will comply to the instructions. If the motorists leave the tunnel, it is most probable that the engines will be turned off because the motorists will lock their cars and take the keys with them.

2.4.4 Absorption of dangerous substances in the body

Only CO is considered to be important in the exposure to dangerous substances because other dangerous substances only have an effect after long exposure times. Deterioration in visibility is considered acceptable because the traffic is stationary and traffic safety is no longer concerned. Odour pollution is considered acceptable because it is not a question of "comfortable" escape. Escape from the tunnel does not happen very often. The only requirement is that the public must leave the tunnel under their own steam.

The length of the escape route is determined by the site of the obstruction. It is assumed that the accident can occur at any place in the length of the tunnel, in which it is assumed that the chance of this is the same.

The speed of escape from the tunnel and the physical effort together with the concentration of CO determine the quantity of Hb-CO in the blood. The volume of CO absorbed during the delay period is also important, even though the activity when waiting is "sitting".

The average walking speed is determined in km/h; this also applies to invalids and elderly people who are helped to leave the tunnel on foot or in another way.

From the safety viewpoint it is assumed that the percentage of Hb-CO in the blood must be low enough not to obstruct escape from the tunnel. For these reasons the limit of Hb-CO in the blood is kept at 10%. This value will not cause most motorists any problems. It is assumed that heart patients will feel some pain. Since this situation will only arise in the event of a disaster, it is considered acceptable.

2.5 FIRE

2.5.1 General

As the result of an accident a fire can arise in the tunnel as well as on the open road. There is a great difference between the consequences of a fire in the tunnel and on the open road. On the open road combustion gases can disperse while in addition oxygen required for combustion can flow in from all sides. Furthermore lower temperatures will arise due to secondary mixing with the cool outside air. Due to these factors the temperature at the source of a fire in the open air will be considerably lower than that of a fire of equal magnitude in a tunnel. The speed of vaporization of gases will also be faster due to the higher temperatures arising in the tunnel, as a result of which the intensity of such a fire will be considerably greater.

The basic assumption for the "fire" scenario is a total obstruction of the tunnel tube as the result of a disaster in which fire breaks out. The traffic will come to a complete standstill and will fill the whole tunnel from the site of the disaster after a short or long time.

As a result of the fire the motorists will escape from the tunnel immediately and therefore will not wait, as in the "escaping motorist" scenario.

2.5.2. Escape corridor

An escape corridor is present between the two tunnel tubes in most modern tunnels which have been opened to the transport of dangerous substances. Since this provision is not, however, always present and in addition it is not always certain to what extent the public makes use of this provision, it was decided to opt for an unambiguous description of the "fire" scenario by assuming that the motorist does *not* make use of the escape corridor which may be present.

2.5.3 Direction of escape and delay period

Escape in the direction of the scene of the disaster is considered to be impossible, so that the motorists must leave the tunnel on foot in the direction of the tunnel entrance. The control room gives instructions via a loudspeaker system to turn off the engine and leave the tunnel on foot. To make these instructions understandable, the noise from the ventilators must not be higher than 100 dB(A) (see Chapters 12 and 14 for more information). Due to the panic situation it is uncertain to what extent the public follows instructions given via the loudspeaker system. The instructions given by the control room speaker system instruct the motorist to turn off the engine. If the motorists leave the tunnel, it is most probable that several engines will be turned off and that the motorists will take their keys with them. The people nearest to the disaster will try to leave the tunnel in panic as a result of which a large number of engines will be left running. In addition it can be assumed that the motorists who are stranded a long distance from the accident will be given the opportunity to turn off their engines and to lock their cars. Apart from that it is clear from this that it will be fairly impossible for members of the emergency services to clear the tunnel in the opposite direction within a reasonable time because many cars will have been locked.

2.5.4 Absorption of dangerous substances in the body

Since fire very seldomly happens no requirements have been made with respect to the absorption of dangerous substances. Deterioration in visibility is considered acceptable because the traffic is stationary and traffic safety is no longer concerned. Odour pollution is considered acceptable because it is not a question of "comfortable" escape. Escape from the tunnel does not happen very often. The only requirement is that the public must leave the tunnel under their own steam. In long tunnels (longer than 2,000 m) in particular attention must be paid to the health aspect, if this requirement is to be fulfilled.

The length of the escape route is determined by the site of the obstruction. It is assumed that the accident can occur at any place in the length of the tunnel, in which it is assumed that the chance of this is spread evenly.

The average walking speed is taken to be 6 km/h; this also applies to invalids and elderly people who are helped to leave the tunnel on foot or in another way.

2.5.5 Magnitude of the fire

Three aspects are very important in a fire in a tunnel which strongly determine the magnitude. These are: firstly the magnitude of the fire, secondly the place of the fire and thirdly the direction of the ventilation current. These important parameters are described below.

A calculation model has been developed by the Centre for Fire Safety TNO-Construction in which the temperatures, quantities of smoke and the combustion pressures arising in a fire in a tunnel can be determined. The calculation has been worked out for three different fires.

1. A "small" fire, in which a car is completely burnt.

The heat production of a car is taken to be 0.35 MW/m². With a surface area of 6 m² the total intensity of the fire is 2.1 MW and the estimated duration of the fire is 25 minutes. The intensity of the radiation is such that a fireman dressed in protective clothing can get to within a few metres of the source of the fire, so that fire fighting does not create a problem. The temperature of the source of the fire with a ventilation speed of 1.5 m/s. Thus the damage to the tunnel interior and the amount of soot will remain limited.

None of the boosters will be impaired by the increase in temperature. These are heat resistant up to temperatures of 250 to 300°C lasting for 1 hour. A ventilator can be damaged only if the fire is right under it; the chance of this, however, is small.

2. A "medium-sized" fire, in which a goods vehicle loaded with wood is completely burnt. The heat production of the lorry is taken to be 1 MW/m². Assuming that the surface area of the source of the fire is 100 m², the total intensity of the fire is 100 MW. The intensity of the radiation is such that it is reasonable to assume that fire fighting is possible at a distance of 10 to 20 m. This assumes that protective clothing is worn. The temperature of the fumes is about 800°C at a distance of 50 m from the source of the fire with a ventilation speed of 1.5 m/s. Besides soot formation it can be expected that the tunnel interior will be damaged.

Boosters at a distance of 150 to 300 m downstream from the fire will be damaged by the high temperatures. There is a 100% chance of these boosters breaking down.

3. A "large" fire in which a tanker loaded with 50 m³ petrol is completely burnt.

The heat production of the tanker is taken to be 2.0 MW/m^2 . With a surface area of 150 m² the total intensity of the fire is 300 MW, the total length of time of the fire is 2 hours. Although the temperatures of the incoming combustion air are barely higher than the outside air temperature, the radiation intensity at low ventilation speeds at a distance of 10 m can be expected to be so high that such a sheet of flames would not be able to be approached up to this distance. For example: at 1m/s the radiation intensity at 10 m is 69 kW/m², at 20 m it is 20 kW/m² and at 40 m it is 3 kW/m².

If the ventilation speed increases to 3 m/s, then the radiation intensities will be 1 kW/m², 0.6 kW/m² and 0.5 kW/m², respectively. The difference in radiation intensities at a ventilation speed of 1 m/s and 3 m/s can be explained by the recirculation of the hot combustion gases at the lower speed. On the basis of the figures given fire fighting would appear to be possible up to a very short distance from the source of the fire provided that protective clothing is of course worn. Putting water canons into operation at a short distance away would appear to offer a practical possibility.

The temperature of the smoke at the source of the fire is very high, namely more than 1,400°C. At a distance of 20 m the temperature of the smoke at a

ventilation speed of 1.5 m/s is 1,400°C. Damage to the interior of the tunnel will be considerable over a large distance in the downstream direction of the fire. Increasing the ventilation speed produces higher temperatures of the fumes over an even greater distance from the source of the fire. This temperature can only be decreased slightly by increasing the amount of "fresh" air to a large extent, namely by 2 to 3 times the normal ventilation capacity, however, not enough to restrict damage to some extent. Such amounts of air imply a very large capacity of the ventilation system and are not feasible on practical and economic grounds.

Depending on the ventilation speed it is assumed that there is a 100% chance that all boosters will be damaged over a distance of 300 to 500 m as a result of the high temperatures of the smoke.

2.5.6 Choice of size of the fire

It is clear that the "large" fire provides the normative criteria. Which of the sizes of fire described will be chosen depends to a large extent on the nature of the tunnel. If a tunnel is concerned which has been opened to the transport of dangerous substances, then it is wise to think in terms of the "large" fire. Tunnels in urban areas or on secondary roads where the transport of dangerous substances is forbidden can be confined to the "medium-sized" fire.

In the development of the probabilistic calculation method the "large" fire is assumed. The calculations made by the Centre for Fire Safety TNO- Construction were also based initially on the "large" fire. At a later stage the probabilistic calculation method will also be worked out for the "medium-sized" fire and these calculations will be made by TNO.

High temperatures must be taken into account in the design of a ventilation system especially in the "large" fire . A global calculation is made to get some impression of the volume of combustion gases released. With longitudinal ventilation at a speed of 1.5 m/s the required volume of combustion air is roughly 88 m³/s and the volume of associated combustion gases is 440 m³/s. As a result of the increase in temperature expansion is 5-fold at a ventilation speed of 1.5 m/s. At a ventilation speed of approximately 5 m/s expansion is 3-fold. The correct quantities must be determined by a computer program, which has been developed by the Centre for Fire Safety TNO-Construction.

Besides the high temperatures which arise from a fire in a tunnel the volume of oxygen required for combustion must also be considered. A limited supply of

oxygen has the consequence that combustion is incomplete: the fire is "suffocated". As a result of this unburnt gases at a high temperature flow through the tunnel which will ignite spontaneously as soon as there is enough oxygen present. Depending on the concentration and volume of the combustible gas this ignition can even be explosive. Both these effects are decidedly unacceptable so that it must be possible to create a sufficient flow of ventilation at all times to ensure complete combustion. As shown in the abovementioned rough calculation the required amount of air of combustion is relatively small compared to the large amount of combustion gases. The volume of air of combustion could be supplied by a small number of ventilators, were it not for the fact that the requirement of driving the combustion gases in one direction must be met. Meeting the requirement of the minimum volume of air of combustion is simpler than meeting the requirement of discharging all the combustion gases in one direction. The reason for this lies in the drop in pressure over the source of the fire. To be able to discharge the energy of the source of the fire in one direction a difference in pressure is necessary which can rise to 140 Pa for the "large" fire at a ventilation speed of 5 m/s. This drop in pressure arises in the development stage of the fire and subsides as the fire approaches a stable state. This pressure difference must also be supplied by the ventilation system in order to meet the requirement that all combustion gases must be discharged to one end of the tunnel. See section 5.6 on "Ventilation systems and fire" for more information.

2.5.7 Site of the fire

The chance of an accident and thus a fire is considered to be evenly spread over the length of the tunnel.

The site of the fire is of essential importance to the consequences of the fire on the tunnel construction and tunnel installations. Depending on the type of ventilation system the site of the fire is more or less important. The site of the fire is not critical if an injector system has been installed with an injector near the entrance because the operation of the injector will not be affected by the fire. If a system with boosters has been installed, the ventilators in the downstream direction of the fire will be break down after a short or long time. The booster's resistance to high temperatures has been restricted for technical reasons to 250 to 300°C for 1 hour. After which they break down and can no longer contribute to the maintenance of the flow of ventilation. The temperatures which arise downstream from the fire is largely dependent on the size of the fire and the distance from the source of the fire. It is conceivable that all the ventilators can keep

operating in a "small" fire. In the event of a "mediumsized" fire it must be shown from a separate temperature calculation made by the TNO program to what extent the temperature causes the break down of the boosters. At the moment it is supposed that the boosters at a distance of 150 to 300 m from the fire will break down due to the high temperatures. In the case of a "large" fire all the boosters within a distance of 300 to 500 m downstream from the source of the fire will break down. These assumptions apply to the usual tunnel length of 1,000 m and a cross section of 50 m^2 . With longer tunnels and different cross sections each case must be looked at individually to see to what extent the distance from the source of the fire works in a sufficiently reducing way to supply a satisfactorily low temperature for the ventilators at positions further from the source of the fire.

The temperature of the combustion gases can be lowered by increasing the air ratio. The volume of air required for the "small" and "medium-sized" fires is such that it can be supplied by a "normal" sized ventilation system. This can certainly be expected to have a favourable effect on "small" and "mediumsized" fires, so that a temperature of below 300°C will be apparent also in the area close to the fire. In the "large" fire the volume of air required is so large that it cannot be supplied by a normal ventilation system. The breakdown of boosters within a distance of 300 to 500 m downstream from the fire due to the high temperatures is unavoidable. Only in longer tunnels will more boosters remain working.

By placing several of these boosters close to the tunnel entrance and to let them work as open injectors it is possible to prevent them from breaking down in the event of fire, unless the site of the fire is right under this injector. Because the available space in the proximity of the entrance to the tunnel is restricted, all the boosters required cannot be placed there. In addition the resistance of the tunnel must not be too high to prevent a back flow. Therefore a combined solution is chosen, namely several boosters working as an open injector and the rest distributed over the length of the tunnel. For more information see section 5.6.4 "Longitudinal ventilation".

2.5.8 Reversible longitudinal ventilation systems

It can be an advantage to be able to reverse the direction of ventilation in the event of fire in the tunnel. It will certainly not be useful in all situations but as described below it is certainly advisable to make the system reversible. The normative fire is the "large" fire because a large number of boosters will be destroyed downstream of this sort of fire. If a reversible ventilation system is assumed, the worst site for the fire would be the middle of the tunnel or a quarter of the distance from the tunnel entrance, if reversal of the direction of ventilation is not possible. The normal direction of ventilation is always in the direction of the traffic towards the tunnel exit.

A solution to the breakdown of ventilators in short tunnels is therefore being sought by placing part of the ventilation capacity at the beginning of the tunnel. A system with an open injector is therefore extremely suitable for this.

2.5.9 Direction of the flow of ventilation

To make fire fighting possible and to reduce the amount of non-material damage as much as possible a system is preferred which drives the combustion gases to one end of the tunnel. For the "small" fire and the "medium-sized" fire only a small volume of air of combustion is necessary. However, to drive all the combustion gases to one end, the drop in pressure over the source of the fire must also be overcome. The quantities of air and the drop in pressure over the source of the fire are considerably larger in the "large" fire. See section 7.10.3 "Drop in pressure over the source of the fire" for more information.

In all situations it is assumed that the tunnel tube downstream from the fire can be cleared of traffic and can be used to discharge the combustion gases, albeit with considerable material damage. The consequence of this assumption is that a traffic monitoring system must be installed which makes sure that no traffic jams are formed because of traffic on the section of the road after the tunnel. This can be achieved by regulating the flow of the traffic by using traffic lights *in front of* the tunnel.

Longitudinal ventilation is not advisable for longer tunnels with two-way traffic due to the increased risk to the stranded motorist in the case of fire in the tunnel. See section 5.6 "Fire and ventilation systems" for more information.

3. EXHAUST FUME EMISSIONS (R.C. Rijkeboer)

3.1. GENERAL

It has already been stated in the introduction that attention will be paid to the emission of different dangerous components in the exhaust fumes. The extension with respect to the previous recommen-dations concerns the substances benzene (C_6H_6) and soot (particulate emission). Future developments are also taken into account.

The determination of the emissions has been carried out by using a calculation model which is available at the Institute for Road Transport TNO. The results of the emission calculations are given in graphs.

The results of this chapter together with those of Chapter 4 "Traffic lane capacity" show the production of the quantity of dangerous substances. For this reason these two chapters are connected to each other with respect to the classification of vehicle categories.

The chapter ends with a calculation example.

3.2. VEHICLE CATEGORIES

The following components are considered with respect to emissions of dangerous substances:

- carbon monoxide (CO)
- benzene (C_6H_6)
- nitrogen dioxide (NO_2)

- particles (particulate emission)

Furthermore, attention will be given to visible smoke; this is connected to the mass emission of particles.

The following vehicle categories are distinguished:

- cars with petrol engines without catalytic converter (15-04)
- cars with petrol engines with regulated three-way catalytic converter (US '83)
- cars with diesel engine (Dies)
- light goods vehicles of 3.5 to 10 gross metric tons (HD 1)
- medium-sized goods vehicles of 10 to 16 gross metric tons (HD 2)
- heavy goods vehicles of more than 16 gross metric tons (HD 3).

For cars which run on LPG the values for cars with petrol engines can be used. Light commercial vehicles (smaller than 3.5 gross metric tons) can be reckoned as 1.5 cars running on the same fuel.

Cars in the Netherlands must all meet the minimum emission requirements of EEC Regulation 15 with respect to the emission of dangerous substances. Since October 1985 amendment 04 of Regulation 15 has applied (15-04). There are also older cars on the road at the present time which were built according to "15-03" and even, albeit a small percentage of "15-02". For future tunnels it seems to be acceptable to only take account of cars which meet the "15-04" regulation. As of 1 January 1993 only cars may be sold in the EC which meet a guideline considered to be just as strict as the American emission requirements (US '83) which apply at the moment. Approximately 2/3 of the new sales in the Netherlands are already made up of this type of car. These cars are equipped with regulated three-way catalytic converters. In the transfer situation cars were sold for several years with unregulated catalytic converters and with optimized conventional techniques ("clean" without catalytic converter). The simplest thing to do is not to include them in the composition of the future fleet of cars and to assume that they meet, proportionately distributed, the emission requirements according to "15-04" and "US '83".

Heavy goods vehicles (HD = heavy duty) are divided into three categories:

- goods vehicles of 3.5 to 10 gross metric tons.

These are in general single vehicles. The average gross weight is taken to be 7 metric tons and the average loaded weight to be 5 metric tons. This category represents approx. 20% of the goods vehicle traffic performance based on the kilometres travelled.

- goods vehicles of 10 to 16 gross metric tons. It is assumed that approx. 1/3 of these vehicles have a trailer. Coaches and buses are also included in this category and are considered to be single vehicles for the purpose of these recommendations. The average gross weight is 17 metric tons. The average loaded weight is taken to be 12 tons. This category represents 25% of the traffic performance by goods vehicles, 5% of which consists of buses and coaches.
- goods vehicles of more than 16 gross metric tons. It is assumed that 2/3 of these have trailers. Furthermore, the articulated vehicle falls into this category. The average gross weight comes to 33.5 tons with an average loaded weight of 23.5 tons. This category represents approx. 55% of the goods vehicle traffic performance, 35% of which consists of articulated vehicles.

The percentages of the goods vehicle traffic given above are national averages. There can of course be local variations in the percentages due to local factors.

3.3. EMISSION DETERMINATION

An emission model is used to determine the emissions. For cars this model gives reasonably reliable results for carbon monoxide (CO), hydrocarbons (HC) and nitrogen oxides (NO_x) . In the emission calculation for cars with catalytic converters the aging of the catalytic converter is taken into account. The emission of benzene (C_6H_6) is determined by assuming that benzene makes up 3% of the total HC emission in petrol engines and approx. 1.5% of the total HC emission in diesel engines. These percentages are supported by research studies reported in the literature. NO₂ emission is determined by assuming that it makes up 10 to 20% of the NO_x emission from petrol engines according to a sliding scale (less at higher speeds) and 15 to 20% from diesel engines. These percentages are based on tests made at the Institute for Road Transport TNO. The emission of particles by diesel engines is determined by assuming that particulate emission is roughly 4.7 g per kg of fuel burnt. This value has been taken from the literature. All this implies that the emission values for C₆H₆, NO2 and particles are very approximate and indicate no more than an order of magnitude especially with respect to the soot particles.

For heavy goods vehicles a model calculation for fuel consumption is taken as a basis, in combination with global emission factors for CO, HC, NO_x and particles in g per kg of fuel burnt. The resulting values therefore have a large margin of error. The emission of benzene is taken to 3% of the total HC emission. Based on measurements taken in the Drecht tunnel it is assumed that the emission of NO₂ is roughly 17% of the NO_x emitted. Emission calculations were made for the following speed ranges:

- 5 to 15 km/h variable speed
- 20 to 50 km/h constant speed
- 70 to 120 km/h constant speed.

It can be assumed that between 10 and 25 km/h the speed gradually transfers from strongly variable to constant. In the case of CO and benzene the low speed ranges are a determinative factor for the need of ventilation. The higher speed ranges can also be a determinative factor for NO_2 and particles because emission increases progressively with speed. A high

speed range has therefore also been worked out for these substances.

The calculations have been made for a flat road and a sloping road with a gradient of +4%. At a gradient of -4% the driving force ensuing from the negative gradient resistance is greater than the driving force required. Because the model does not provide for this, estimates have been made based on emissions at very low speeds on a flat road. Furthermore, it appears that CO is mainly emitted from cars of the "15–04" type. Benzene is a problem in "15–04" cars as well as in heavy goods vehicles whereas the emission of particles is only a problem in diesel engines. The results of the model calculations for a flat road and for a sloping road with a gradient of +4% are given in Figures 3.1 to 3.10 for carbon monoxide (CO), benzene (C₆H₆), nitrogen dioxide (NO₂) and particles, in that order:

- Figure 3.1 : CO emission cars, 0-50 km/h
 Figure 3.2 : CO emission heavy goods vehicles 0-50 km/h
 Figure 3.3 : C₆H₆ emission cars, 0-50 km/h
 Figure 3.4 : C₆H₆ emission heavy goods vehicles, 0-50 km/h
 Figure 3.5 : NO₂ emission cars, 0-50 km/h
 Figure 3.6 : NO₂ emission heavy goods vehicles, 0-50 km/h
 Figure 3.7 : NO₂ emission cars, 80-120 km/h
 Figure 3.8 : NO₂ emission heavy goods vehicles, 70-100 km/h
- Figure 3.9 : Particulate emission, diesel cars, 0-50 km/h
- Figure 3.10 : Particulate emission, diesel cars, 70-120 km/h.



FIGURE 3.1: CO emission cars, 0 - 50 km/h



FIGURE 3.2: CO emission heavy goods vehicles, 0 - 50 km/h



FIGURE 3.3: C_6H6 emission cars, 0 - 50 km/h



FIGURE 3.4: C_6H6 -emission heavy goods vehicles, 0 - 50 km/h



FIGURE 3.5: NO2 emission cars, 0 – 50 km/h



FIGURE 3.6: NO2 emission heavy goods vehicles, 0 - 50 km/h



FIGURE 3.7: NO2 emission cars, 80 - 120 km/h



FIGURE 3.8: NO₂ emission heavy goods vehicles, 10 - 100 km/h



FIGURE 3.9: Particulate emission diesel cars, 0 – 50 km/h



FIGURE 3.10: Particulate emission diesel cars, 70 - 120 km/h

3.4 EMISSION FACTORS

The following are the simplified emission ratios based on the model calculations. Where v stands for the vehicle speed in km/h.

TABLE 3.1:

CO emission in g/h per vehicle (0-50) km/h)

vehicle category	speed category		flat road	gradient – 4%	gradient + 4%
15-04	0–50	km/h	250	250	250+3v
US-'83	0–50	km/h	40	40	40
Diesel	0-50	km/h	40	40	40
HD1	0–10 10–25 25–50	km/h km/h km/h	35+2,5v 86,7-2,67v 0,8v	35-1,4v 35-1,4v 0	35+4v 98,3-2,33v 1,6v
HD2	0-10 10-25 25-50	km/h km/h km/h	60+5v 162,5-5,25v 1,25v	60-2,4v 60-2,4v 0	60+9v 193,3-4,33v 3,4v
HD3	0–10 10–25 25–50	km/h km/h km/h	65+7,5v 210-7v 1,4v	65–2,6v 65–2,6v 0	65+13v 243,5-5,33v 4,4v

TABLE 3.2:

 C_6H_6 emission in g/h per vehicle (0-50 km/h)

vehicle category	speed category		flat road	gradient – 4%	gradient + 4%
15-04	0–90	km/h	2	2	1,75+0,01v
US'83	0–50	km/h	0,2	0,2	0,2
Diesel	0–50	km/h	0,2	0,2	0,2
HD1	0-10 10-50	km/h km/h	0,75 0,75	0,6 0,6	0,5+0,05v 5
HD2	0–10 10–50	km/h km/h	1,50 1,50	1,25 1,25	1+0,1v 2
HD3	0-10 10-50	km/h km/h	3,50 3,50	2,50 2,5	2,5+0,25 1

TABLE 3.3:

vehicle category	speed category		flat road	gradient – 4%	gradient + 4%
15-04	0-10 10-50	km/h km/h	0,125v 0,8+0,04v	0,25 0,25	0,30v 1,5+0,15v
US'83	0–50	km/h	0,015v	0,005	0,05v
Diesel	0–10 10–50	km/h km/h	1,25+0,08v 1,75+0,03v	1,25 1,25	1,0+0,2v 2,0+0,1v
HD1	0–50	km/h	15+0,3v	15	15+1,0v
HD2	0-50	km/h	25+0,6v	25	25+2,0v
HD3	0–50	km/h	40+0,8v	40	40+3,6v

 NO_2 emission in g/h per vehicle (0-50 km/h)

TABLE 3.4:

NO₂ emission in g/h per vehicle (70-120 km/h)

vehicle category	speed category	flat road	gradient -4%	gradient +4%
15-04	70–120 km/h	2,5 . 10 ⁻⁶ v ³ + 2,5	1,0 . 10 ⁻⁶ v ³	4 . 10 ⁻⁶ v ³ + 9
US'83	70–120 km/h	$2,25 \cdot 10^{-6} v^3$	0,6 . 10 ⁻⁶ v	5,4 . 10 ⁻⁶ v ³
Diesel	70–120 km/h	4.10 ⁻⁶ v ³ + 0,04v	1,6 . 10 ⁻⁶ v ³ + 0,016v	4.4 . 10 ⁻⁶ v ³ + 0,12v
HD1	70–120 km/h	$140.10^{-6}v^3 + 0.3v$	$15 \cdot 10^{-6} v^3$	140 . 10 ⁻⁶ v ³ + 1,0v
HD2	70–120 km/h	140.10 ⁻⁶ v ³ + 0,6v	35 . 10 ⁻⁶ v ³	140 . 10 ⁻⁶ v ³ + 2,4v
HD3	70–120 km/h	$140.10^{-6}v^3 + 1.0v$	$70.10^{-6}v^3$	$140 \cdot 10^{-6}v^3 + 4,2v$

TABLE 3.5:Particulate emission in g/h per vehicle (0-50 km/h)

vehicle category	speed category	flat road	gradient -4%	gradient +4%
Diesel	0–50 km/h	2 + 0,1v	0	3 + 0,2v
HD1	0–50 km/h	8	0	8 + 0,3v
HD2	0–50 km/h	15	0	15 + 0,6v
HD3	0–50 km/h	25	0	25 + 1,3v

TABLE 3.6:

Particulate emission in g/h per vehicle (70-120 km/h)

vehicle category	speed range	flat road	gradient -4%	gradient +4%
Diesel	70–120 km/h	0,5 - 2,5	0,3v - 2,5	0,7v - 2,5
HD1	70–120 km/h	$50 \cdot 10^{-6} v^3 + 0,1 v$	50 . 10 ⁻⁶ v ³ - 0,2v	$50 \cdot 10^{-6} v^3 + 0,4 v$
HD2	70–120 km/h	$50 \cdot 10^{-6} v^3 + 0,2 v$	50 . 10 ⁻⁶ v ³ - 0,4v	$50 \cdot 10^{-6} v^3 + 0.8 v$
HD3	70–120 km/h	50 . 10 ⁻⁶ v ³ + 0,4v	50 . 10 ⁻⁶ v ³ – 0,8v	50 . 10 ⁻⁶ v ³ + 1,6v

N.B.:

Set negative values at 0!

3.5 DETERIORATION IN VISIBILITY

Deterioration in visibility in not an emission in the sense of the aforementioned. The calculation is therfore somwhat different. The specific light exclusion factor k in m^{-1} is the criterion for a deterioration in visibility. This factor behaves like a smoke concentration. The factor k reacts in a linear way to rarefication. In the definition of:

- $k_m =$ smoke "concentration" in the exhaust fumes of the engines (m^{-1})
- $k_1 = \text{smoke "concentration" in the tunneltube (m⁻¹)}$
- Q_m = output rate of engine exhaust fumes (m³/h)
- Q_v = flow rate of ventilating air in the tunnel for one vehicle (m_3/h) it applies that:

$$\mathbf{k}_{\mathrm{m}} \ge \mathbf{Q}_{\mathrm{m}} = \mathbf{k}_{\mathrm{l}} \ge \mathbf{Q}_{\mathrm{v}} \tag{3.1}$$

therefore:

$$Q_v = (k_m/k_l) \times Q_m$$
 (3.2)

Where Q_v is the required minimum output rate of ventilating air for one vehicle and k_t is the maximum permissible deterioration in visibility.

An empirical relationship now applies between the k value and the soot concentration (based on an assumed particle size distribution) which is:

$$k = (7 \text{ to } 8) \times C_d$$

in which:

Cd	=	particle concentration in the	
-		exhaust fumes	(g/m ²)
k	=	the smoke concentration	(m^{-1})

This means that the empirical factor certainly is not dimensionless but has the dimension m_y/g .

The total particulate emission in g/h is:

$$E_{part} = C_d \times Q_m \tag{3.3}$$

A connection can now be made bewteen the k value and the particulate emission, if k is taken to be 7.5 x C_d , as follows:

$$k_m \ge Q_m = 7.5 \ge C_d \ge Q_m = 7.5 \ge E_{part}$$
 (3.4)

The deterioration in visibility can thus be deduced from the particulate emission in g/h. The ventilation requirement in m_3/h for one vehicle is therefore:

$$Q_v = (1/k_t) \times 7.5 \times E_{part}$$
 (3.5)

Permissible deterioration in visibility

Only a PIARC recommendation is available for the permissible deterioration in visibility. Therefore it is recommended that this is employed. This recommendation assumes a light transmission T over a distance of 100 m. This results in a permissible k value which is different for the speed ranges 0-40 km/h and above 40 km/h.

The permitted levels are as follows:

v < 40 km/h:T $_{100m} = 40\% \implies k_{max} = 4 \text{ x } 10^{-3} \text{ m}^{-1}$ $v \ge 40 \text{ km/h:}$ T $_{100m} = 48\% \implies K_{max} = 3.2 \text{ x } 10^{-3} \text{ m}^{-1}$

3.6 CALCULATION EXAMPLE

Finally a calculation example is given at the end of this chapter. To determine the composition of the traffic a distribution of the volume of traffic is necessary. In this calculation example the distribution of the volume of traffic is taken to be equal to the distribution of the traffic performance measured in terms of kilometres travelled. The distribution of the traffic capacity was taken from the CBS (Central Statistical Bureau) figures for 1984. This has been converted into a percentage distribution per vehicle category shown in Table 3.7.

TABLE 3.7:

Percentage distribution of the traffic capacity of cars, vans and goods vehicles over types of road (1984)

vehicle category	total	built-up area	secondary road	motorway
Car				
total petrol/LPG diesel	<u>1.000</u> 0,884 0,116	0,319 0,282 0,037	0,392 0,347 0,045	0,289 0,255 0,034
Van total petrol/LPG diesel	<u>1.000</u> 0,516 0,484	0,739 0,381 0,358	0,165 0,085 0,080	0,096 0,050 0,046
Goods veh. total HD 1 (3,5-10 t)	<u>1.000</u> 0,211	0,199	0,380	0,421
HD 2 (10-16 t) HD 3 (> 16 t)	0,323 0,466	0,094 0,059	0,126 0,173	0,103 0,234

A percentage distribution of traffic performance per type of road is given in Table 3.8.

TABLE 3.8:

Percentage distribution of traffic performance per type of road over vehicle categories and subcategories (1984)

vehicle category	total	built-up area	motorway
Car			
total	0,875	0,830	0,884
petrol/LPG	0,773	0,733	0,781
diesel	0,102	0,097	0,103
Van			
total	0,060	0,132	0,020
petrol/LPG	0,031	0,068	0,010
diesel	0,029	0,064	0,010
Goods veh.			
total	0,065	0,038	0,096
HD 1 (3,5-10 t)	0,014	0,009	0,019
HD 2 (10-16 t)	0,021	0,018	0,024
HD 3 (> 16 t)	0,030	0,011	0,053
Totaal	1,000	1.000	1,000

For the main categories cars and vans it is assumed that the distribution over the type of road is the same for the subcategories petrol and diesel vehicles. This is in actual fact not the case (the proportion of diesel vehicles will be higher than average on the motorway and lower than average in the urban areas) but information about the actual distribution is not available. Take the case of a tunnel on a urban road. Assume that this must be calculated for 1995 and that at that time approx. 35% of the petrol/PLG cars meet the "US'83" standard (the replacement speed of the fleet of cars is approx. 10% per annum and at present approx. 70%of which consists of "US'83" cars). Vans count as 1.5 cars and those which run on petrol/LPG fall into the "15-04" category. The percentages (for urban traffic) are given in Table 3.9. The percentages for vans have been multiplied by 1.5 so that the total comes to more than 100% (column 1). The percentages corrected to 100% are given in column 2. The vans are added to the cars to give the weighted factors in column 3.

TABLE 3.9:

Percentage distribution of vehicle categories for the emission calculation. Built-up area; proportion of "US'83" cars : 35%.

vehicle category	uncorrected	corrected	weighted factor
Car			
15-04	0,476	0,447	0,543 *
US'93	0,257	0,241	0,241
diesel	0,097	0,091	0,181 *
Van			
petrol/LPG	0,102 (1,5x)	0,096	
diesel	0,096 (1,5x)	0,090	
Goods veh.			
HD 1	0,009	0,008	0,008
HD 2	0,018	0,017	0,017
HD 3	0,011	0,010	0,010
Totaal	1,066	1,000	1,000

* cars and vans

Assume that the descending and ascending gradients are -4% and +4%, respectively. The emission factor can now be calculated per category for each speed from the equations in paragraph 3.4.

This has been done for CO and NO_2 for a speed of 10 km/h. The results are given in Table 3.10. These emissions have been multiplied by the weighted factors given in Table 3.9 (3rd column) and added up.Assume also that the tunnel has equal gradients 0.5 km long and a flat section in between 0.25 m long.

Assume in addition that there are 3 lanes per tunnel tube and that at this speed there are 108 vehicles per km of traffic lane. The total CO emission per tunnel tube is therefore:

- $CO = 3 \times 108 (0.5 \times 153.8 + 0.25 \times 156.4 + 0.5 \times 174.0)$
 - = 3 x 108 x 203 = 65,772 g/h = 66 kg/h

The emission of NO_2 is:

- $NO_2 = 3 \times 108 (0.5 \times 1.32 + 0.25 \times 2.24 + 0.5 \times 4.02)$
 - = 3 x 108 x 3.23 = 1,046 g/h = 1.05 kg/h

In the same way it can be calculated that the total particulate emission $E_{put} \approx 500$ g/h. It follows that:

$$k_m \ge Q_m = 7.5 \ge E_{oart} = 7.5 \ge 500 = 3500.$$

With a total deterioration in visibility of:

 $k_t = 4 \times 10^{-3} m^{-1}$

this produces a total ventilation requirement of:

$$Q_t = \frac{3750}{4 \cdot 10^{-3}} = 937.500 \text{ m}^3/\text{h}$$
TABLE 3.10:

		gradient -4%		flat	road .	gradient +4%	
со	weghted factor	emission	weighted emission	emission	weighted emission	emission	weighted emission
15-04 US'83 diesel HD 1 HD 2 HD 3	0,543 0,241 0,181 0,008 0,017 0,010	250 40 40 21 36 39	135,8 9,6 7,2 0,2 0,6 0,4	250 40 40 60 110 140	135,8 9,6 7,2 0,5 1,9 1,4	280 40 40 75 150 195	152,0 9,6 7,2 0,6 2,6 2,0
			153,8		156,4		174,0
NO ₂							
15-04 US'83 diesel HD 1 HD 2 HD 3	0,543 0,241 0,181 0,008 0,017 0,010	0,25 0,005 1,25 15 25 40	0,14 0,001 0,23 0,12 0,43 0,40	1,25 0,15 20,5 18 31 48	0,68 0,04 0,37 0,14 0,53 0,48	3,0 0,5 3,0 25 45 76	1,63 0,12 0,54 0,20 0,67 0,76
			1,32		2,24		4,02

Calculation of the weighted emission in g/h of CO and NO_2 (10 km/h)

4. TRAFFIC LANE CAPACITY IN TUN-NELS

(L. Swart)

4.1. GENERAL

To be able to determine the emission from the vehicles in a tunnel insight needs to be gained into the traffic lane capacity. This concerns the density (number of vehicles per km) as well as the subdivision into vehicle categories. This chapter summarizes the way in which the traffic lane capacity is determined based on various studies.

4.2 DENSITY OF 100% CARS

The density of 100% cars as a function of speed can be derived from Table 4.1.

TABLE 4.1:Density of 100% cars

speed	centre to	space in	density
(km/h)	dist. (m)	(m)	(veh/km)
0	6,89	2,60	145,15
5	8,32	4,03	120,19
10	10,06	5,77	99,4
15	12,14	7,85	82,37
20	14,63	10,34	68,35
25	16,94	12,65	59,03
30	19,25	14,96	51,95
40	22,71	18,42	44,03
50	26,17	21,88	38,21

Table 4.1. is based on a vehicle length of 4.29 m for an average car.

To be able to determine the emission of the category cars the density as given in Table 4.1 must be specified further according to the type of fuel.

CBS figures have been used to make this subcategorization. Different criteria have been used for the subcategorization given in Tables 4.2 to 4.4 and will be discussed in sequence. Table 4.5 gives the final conclusion with respect to density according to type of fuel.

The distribution of the number of cars according to

type of fuel is given first. CBS figures for the years 1984 to 1988 included in Table 4.2 are used which relate to the percentage distribution of the number of petrol engines without catalytic converters, diesel engines and LPG engines.

TABLE 4.2:

Percentage distribution of the number of cars according to type of fuel

type of fuel	percentage distribution					
	1984	1985	1986	1987	1988	
petrol engines *	82	81	80	79	78	
diesel engines	6	7	8	9	10	
LPG engines	11	11	12	12	12	
total	99	99	100	100	100	
no. veh.x10^3	4519	4600	4642	4755	4921	

* engines without catalytic converters

The second method of making a distribution according to type of fuel is based on the number of vehicle kilometres also called vehicle performance.

The percentage distribution of the annual number of kilometres travelled by cars according to type of fuel is given in Table 4.3.

TABLE 4.3:

Percentage distribution of the kms travelled by cars according to type of fuel

kms travelled	percentage distribution					
year	1984	1985	1986	1987	1988	1989
petrol engines *	70	68	67	67	66	61,3
diesel engines	12	14	16	16	17	21,9
LPG engines	18	18	17	17	17	16,8
total	100	100	100	100	100	100,0
no. kmsx10^3	65350	64950	68150	71230	75930	-

* engines without catalytic converters.

The last column for 1989 gives the distribution according to type of fuel corrected for the percentage of vans. It appears that almost all vans have diesel engines.

A distribution can also be made based on the number of kilometres travelled on roads outside the built-up area. See Table 4.4.

TABLE 4.4.:

Distribution according to kms travelled outside the built-up area

kms travelled	perc	entage	distrib	ution	
year	1984	1985	1986	1987	1988
national roads	56	56	56	56	-
no. veh.x10^3	45603	46842	50638	54168	-

On the basis of Tables 4.2 to 4.4. the following conclusions and recommendations can be made:

- there were no great changes in distribution according to type of fuel in the period studied.
- the percentage of diesel engines rose at the expense of petrol engines.
- the trend of an increasing use of diesel engines is doubtful, due to the environmental subsidy on catalytic converter engines. It is true that the number of diesel engines rose but the number of kms travelled hardly increased.

Since the development of diesel engines with catalytic converters is still uncertain, the percentage of diesel engines including vans is taken to be 20%.

- the percentage LPG engines is practically constant in number as well as the kilometres travelled. This percentage must be added to that of ordinary petrol engines because as regards emission they are the same.
- it is proposed that the number of kms travelled, also called vehicle performance, and not the number of vehicles is used as the basis for the distribution according to type of fuel.
- the percentage vehicle kilometres travelled on national roads outside the built-up area is constant and amounts to 56% of the total distance travelled.
- it is not possible to determine if cars with diesel engines make more use of national roads outside the built-up area, so this effect is not considered.
- if a correction is made for vans then it seems that the number of kilometres travelled by diesel engines is much higher than would have at first sight been expected.

No information is available about the number of engines with catalytic converters but it is assumed that in the near future "normal" engines will no longer be permitted. It is assumed that over a period of 10 years the present fleet of cars will be replaced. For the period from 1990 to 2000 this means that an annual increase in the percentage of engines with catalytic converters must be reckoned on. This annual percentage of engines with catalytic converters relates to the number of cars with petrol engines. It is realistic to assume an initial percentage of 10% in 1990. The remaining number of petrol-driven cars are considered to have traditional petrol engines or LPG engines.

Table 4.5 has been drawn up based on the aforementioned considerations. This table gives the total car traffic density and the density per type of fuel, depending on travelling speed, in which vans are included.

TABLE 4.5:

Density of 100% cars, including vans, according to type of fuel.

	cars		density	in vehic	cles/km
kpeed (km/ h)	c.t.c. distance (m)	space in between (m)	total (veh/km)	petrol engines with catalic conver- ter	diesel engines (veh/km)
0	6,89	2,60	145,14	8,94	32,96
5	8,32	4,03	120,19	7,4	27,30
10	10,06	5,77	99,40	6,12	22,58
15	12,14	7,85	82,37	5,07	18,71
20	14,63	10,34	68,35	4,21	15,52
25	16,94	12,65	59,03	3,64	13,41
30	19,25	14,96	51,95	3,2	11,80
40	22,71	18,42	44,03	2,71	10,00
50	26,17	21,88	38,21	2,35	8,68

The density of 100% goods vehicles as a function of speed can be derived from Table 4.6

TABLE 4.6:

Density of 100% goods vehicles

speed	c.t.c.	space in between (m)		density
(km/h)	(m)			(veh/km)
0	15,99	3,48	(1,00)*	62,54
5	17,42	4,91	(2,43)	57,41
10	19,16	6,65	(4,17)	52,19
15	21,24	8,73	(6,25)	47,08
20	23,73	11,22	(8,64)	42,14
25	26,04	13,53	()	38,40
30	28,35	15,84	(13,36)	35,27
40	31,81	19,30	(16,82)	31,44
50	35,27	22,76	()	28,35

Table 4.6 is based on a vehicle length of 12.51 m for an average goods vehicle.

4.4. MIXED TRAFFIC

The composition of the traffic is strongly determined by the geographical position of the tunnel. Therefore, before a ventilation calculation is made, the composition of the traffic must be determined first. In order to do this a study must be made which is outside the framework of these recommendations.

The density of mixed traffic is determined by mixing the unmixed categories.

From Tables 4.5 and 4.6 for 100% cars and 100% goods vehicles, respectively the traffic density of mixed traffic can be determined in a simple way from the average centre-to-centre distance of the vehicles according to:

density of mixed traffic =

1000 average c.t.c. distancce

(vehicles/km)

The average centre-to-centre distance in mixed traffic is calculated for each speed in proportion to the composition of the vehicle categories from the separate centre-to-centre distances of unmixed traffic. The following example makes it clear how this calculation is made. Suppose that the composition of the traffic is:

10% goods vehicles and 90% cars.

With stationary traffic the centre-to-centre distances according to Tables 4.5 and 4.6 are 15.99 m and 6.89 m, respectively. From this the average centre-to-centre distance is calculated for stationary traffic as follows:

Average centre-to-centre distance = $(0.1 \times 15.99) + (0.90 \times 6.89) = 7.80 \text{ m}$

The density per km of traffic lane is therefore 1000/7.8 = 128.21 vehicles /km.

of which:

- goods vehicles: 0.1 x 128.21 = 12.8/km - cars: 0.91 x 128.21 = 115.4/km.

The category cars is subsequently divided according to type of fuel. Suppose that 22% of the cars have diesel engines (including vans) and that 10% of the number of cars with petrol engines have catalytic converters.

Then the distribution per km of traffic lane is as follows:

- cars with diesel engines: $0.22 \times 115.4 = 25.4/km$
- cars with petrol engines: 115.4 - 25.4 = 90.0/km
- cars with catalytic converter engines:
 0.1 x 90.0 = 9.0/km
- cars with normal and LPG engines: $0.9 \times 90.0 = 81.0/km$.

The number of units per vehicle category can be determined for each traffic composition required by using the method described above.

The total emission of dangerous substances per km of traffic lane can be determined from the figures found above and the emission quantities from Chapter 3. A calculation program for this is available from the Civil Engineering Division of the Directorate-General for Public Works and Water Management (RWS).

4.5 FUTURE DEVELOPMENTS

The results of the research described in this chapter can be used for the moment with sufficient reliability to determine the density of the traffic, also in the future, provided that information about the composition of the traffic at the location is sufficiently accurate. By using the computer program at the Civil Engineering Division of RWS, several parameters can be changed after which the program works out the vehicle density in detail. By altering the percentage of cars with a diesel engine or an engine with catalytic converter this can be taken into account. This chapter provides enough information to enable the independent development of a similar program.

5. VENTILATION SYSTEMS (L. Swart)

5.1 GENERAL

A lot of research has already been carried out in the field of the ventilation of tunnels. In some cases research was started after accidents, disasters and such like. An example of this is the tunnel renovation programme which was started after a fire in the Velser tunnel in 1978, in which 5 people died and a lot of material damage was caused. In this fire, which as far as size is concerned can be characterized as a medium-sized fire, it was clear that the transverse ventilation system installed in this tunnel was not able to cope with the enormous production of smoke. This information had been known for a long time. The fire confirmed that the volume of combustion gases and smoke cannot be discharged in a controlled way by a "normal" transverse ventilation system. There are a number of reasons for this, two of which will be dealt with here. Firstly the large amount of smoke and secondly a longitudinal ventilation current which is difficult to control due to external factors, the most important of which being the effect of wind on both tunnel openings. This is one of the reasons why transverse ventilation is no longer used in the construction of new tunnels in the Netherlands.

This chapter broadly deals with the ventilation systems used in tunnel technology. Depending on the direction of the ventilating flow of air with respect to the longitudinal axis of the tunnel the ventilation systems are referred to as transverse ventilation, semi-transverse ventilation or longitudinal ventilation.

5.2 TRANSVERSE VENTILATION

Transverse ventilation is the system in which the air supplied as well as the air removed is moved transversely to the longitudinal axis of the tunnel. This circulation is disturbed as soon as external factors are present, which create a longitudinal current, such as: differences in wind pressure on both tunnel openings, atmospheric pressure differences, the traffic, a fire in the tunnel. This means that in practice a flow which is purely transverse to the longitudinal axis of the tunnel will hardly ever occur. A second aspect which attracts attention is that the longitudinal current is difficult to control even if the transverse ventilation system has a larger capacity because there are no compensating forces present in the longitudinal direction.

The concentration of pollution in the air is constant over the length of the tunnel. This system is therefore extremely suitable for application in long tunnels. In principle there is no limit to the tunnel length, if the pollution produced is concerned; but of course technical and economic restrictions apply. For more information refer to section 5.5. "Air pollution and ventilation systems".

Types of transverse ventilation systems

The ventilating air is supplied and extracted through air ducts. The total volume of ventilating air required is considerable especially in long tunnels. As a result the ducts are large and therefore expensive. The air speeds occurring in the ducts determine the required capacity of the ventilation system to a significant extent. In long tunnels the duct system is therefore compartmentalized longitudinally and air is supplied at various places in order to restrict the air speeds in this way. Speeds of 10 to 15 m/s in the air ducts are usual. The ventilators are usually planned near the tunnel openings because they are the easiest to reach.

The supply of ventilating air in the tunnel can be achieved in two ways, namely horizontally or vertically. These principles have advantages and disadvantages. The solution chosen depends on a lot of factors. There is an important difference between the possible solutions in bored tunnels, horseshoe-shaped tunnels and right-angled tunnels. All these tunnel shapes have their specific area of application depending on the situation, the geodetic foundations, etc.

The ventilation solutions given in the following figures are only illustrative and certainly not complete. Only the technical consequences of the ventilation are considered here.

In right-angled tunnel cross sections it is usual that the ventilation ducts are located to the left and right of the tunnel tube (Figure 5.1). This has the advantage that the construction height will be lower and thus the depth position will not be so deep. In this solution the replacement of the transverse cross section is not optimal, there are so-called "stagnant" areas.



FIGURE 5.1:

Transverse ventilation - method 1

The emergency corridor is often combined with the ventilation duct which is located between the two tunnel tubes. The emergency route must be at the level of the road surface making it is easy for the public to reach. This means that the emergency corridor is situated under the ventilation duct. In the event of fire the emergency route must be brought under a small over pressure to keep the emergency route free of smoke. In addition bad visibility due to the strong development of smoke in the tunnel tube must be taken into account in the signs for the doors to the emergency corridor. As long as the smoke is still stratified visibility is best nearer to the road surface. This fact must be taken into account when determining the position of the pictograms.

A second solution is given in Figure 5.2.

The replacement of the transverse cross section is optimal in the solution given in Figure 5.2. In addition in the event of fire smoke is extracted at the right place so that visibility in the tunnel is guaranteed as well as possible.



FIGURE 5.2:

Transverse ventilation - method 2

This solution does not offer any possibility for an emergency corridor at the same level as the road surface. This type of implementation is therefore not used in the Netherlands.

Figure 5.3 shows the third method of transverse

ventilation in schematic form.



FIGUUR 5.3:

Transverse ventilation - method 3

The solution given in Figure 5.3. has been applied in the Velser tunnel. The supply ventilators are capable of being reversed to enable extraction to occur at full capacity in the event of fire. In addition the ventilation system is divided into sections in the longitudinal direction thereby providing the possibility of the section in which the fire occurs extracting air and the adjacent sections supplying ventilating air.

There is no emergency corridor. As already shown in Figure 5.2 this solution does not fulfil the current insights with respect to safety. If transverse ven-tilation is still chosen in the future, the solution given in Figure 5.1 should be preferred.

Figures 5.4 and 5.5. give two examples of transverse ventilation systems with a vertical movement of air.

The above-mentioned solutions are generally applied in bored tunnels or mountain tunnels due to the almost circular or horseshoe-shaped cross section.

A separate tunnel tube is usually made for the emergency route, which is connected to the tunnel tubes by transverse corridors.

The solution given in Figure 5.4 should be preferred in connection with the better extraction of smoke during a fire in the tunnel. In the normal operating situation the solution given in Figure 5.5. is more effective in terms of the extraction of stronger pollutants. Visibility is also better in the tunnel because the scattering of light is lower as a result of the cleaner air at the ceiling of method 5. The advantages and disadvantages should be weighed up before deciding which of these two solutions is preferred.



FIGURE 5.4:

Tranverse ventilation – method 4



FIGURE 5.5: Transverse ventilation – method 5

Although countless other variations are conceivable, this aspect in not gone into any further in the framework of these recommendations.

5.3. SEMI-TRANSVERSE VENTILATION

Semi-transverse ventilation is the system in which the air supplied is supplied transversely to the direction of the longitudinal axis of the tunnel, while the extracted air is removed parallel to the direction of the traffic. It is also possible to think in terms of a reversed semi-transverse ventilation system in which the air supplied flows parallel to the longitudinal axis while the extracted air flows in the transverse direction. Such a system has not yet been applied in the Netherlands. As a consequence of stricter environmental requirements it could be necessary to choose such a solution in the future.

Just as in transverse ventilation, in semi-transverse

ventilation external factors can create a longitudinal current which is difficult to control.

The concentration of pollutants is not constant over the length of the tunnel and increases in the longitudinal direction. Theoretically the concentration of pollutants is lowest in the middle of the tunnel and increases towards both ends of the tunnel. As a result of this tunnel length is restricted by the permissible concentration of pollutants. For more information refer to 5.5 "Air pollution and ventilation systems".

Types of semi-transverse ventilation systems

The most important difference from the transverse ventilation is that only fresh air is supplied via a duct, while the extraction of the polluted air takes place through the tunnel tube. A reversed system can also be chosen in which the polluted air is extracted by ducts and fresh air is supplied through the tunnel tube. As already noted above it may be necessary to build such a system in the future in connection with environmental technical considerations. This system prevents polluted tunnel air from escaping from the tunnel opening and thereby polluting the environment.

In long tunnels the duct system is sizable because of the large quantities of ventilating air so that longitudinal compartmentalization is necessary. The costs in that case are considerable but in all probability lower than in transverse ventilation.

Examples of semi-transverse ventilation systems are given in Figures 5.6. and 5.7 of the horizontal supply and extraction of ventilating air.



FIGUUR 5.6:

Semi-transverse ventilation - method 1

In the solution given in Figure 5.6 fresh air is brought in from the underneath of the tunnel tube. This has the advantage in the normal operating situation that clean air is supplied at the place where the motorists and the emergency workers are. In the event of fire this method of blowing in air is, however, less favourable. Mixing of the smoke occurs resulting in the whole tunnel tube being filled with smoke making the possibility of escape more difficult. It is therefore better to extract the air at the top of the tunnel tube as shown in Figure 5.7.

exhaust		
duct	tunnel tube	
	eshauel duct	exhaust duct kunnel kibe

FIGUUR 5.7:

Semi-tranverse ventilation - method 2

Examples of the vertical supply and extraction of the ventilating air are given in Figures 5.8 and 5.9.



FIGURE 5.8:

Semi-transverse ventilation - method 3

The vertical supply and extraction of the ventilating air is mainly applied in bored tunnels or mountain tunnels. The solution shown in Figure 5.9 should be preferred because in this case the extraction of smoke is better in the event of fire.

The method shown in Figure 5.8 in which the polluted air is extracted via an air duct is more effective if the removal of stronger pollutants is concerned. The method shown in Figure 5.9 in which the supply of fresh air takes place at ceiling level should be given preference in the normal operating situation because the lighting is then in relatively clean air. The advantages and disadvantages of the solutions described should be weighed up before deciding which is preferred.



FIGUUR 5.8: Semi-transverse ventilation – method 3

There are countless other solutions which are conceivable. The solutions described are only given as an illustration in order to give an idea of the problems involved.

5.4 LONGITUDINAL VENTILATION

Longitudinal ventilation is the system in which the ventilating air is supplied as well as extracted in the direction of the longitudinal axis of the tunnel. The air ducts required in both the aforementioned systems are not required for longitudinal ventilation. With longitudinal ventilation the longitudinal current created by external factors can be controlled in a simple way.

The concentration of the pollutants is not constant over the length of the tunnel and increases in the direction of the longitudinal flow. The tunnel length is restricted as a result of this because of the permissible concentration of the pollutants. For more information refer to 5.5. "Air pollution and ventilation systems".

Types of transverse ventilation systems

In the system of longitudinal ventilation the permissible air speeds are not imposed by duct restrictions but by the traffic travelling in the tunnel. In tunnel tubes with two-way traffic the air speeds in the empty tunnel are usually 10 to 12 m/s. Increased concentrations of exhaust fumes must be taken into account from goods vehicles in particular which enter the tunnel against the ventilation current. But as noted elsewhere it is not advisable, on account of safety during a fire, to use longitudinal ventilation in combination with the counter flow of traffic in the normal operating system. In tunnels with one-way traffic the permissible air speed can be higher than the stated 10 to 12 m/s.

The longitudinal current can in principle be created by means of boosters or an injector. A combination of both systems is also possible and offers the best solution in the event of fire. See 5.4.4. for more information.

5.4.1 Longitudinal ventilation with boosters

Boosters are installed in the tunnel tube just outside the clearance space (see Figure 5.10). The operation of these boosters relies on the injection principle. The boosters move a proportion of the tunnel air at high speed so that a driving force is created by the difference in speed of the tunnel air and that of the air flow from the ventilator. This driving force must overcome all types of resistance, such as the effects of wind on the tunnel openings, the input and output losses, the resistance of the tunnel tube, vehicle resistance and thermal effects in the case of fire.



Cross section

Figure 5.10: Longitudinal ventilation with boosters

The total efficiency of the whole ventilation system depends on a large number of factors of which the most important are:

- position of the booster in the cross section
- dimensions of the so-called clearance space profile
- diameter of the air stream flowing out of the booster
- differences in speed of the air from the booster and that of the surrounding tunnel air
- distribution of the tunnel air speed over the transverse section

- distance between the boosters
- use of deflection blades.

The total efficiency of the system is understood to mean the quotient of the power transferred to the tunnel air and the power consumption of the system supplying the flow of air. This is low for a booster system. This is not considered to be problematic because the system only operates for a small number of hours. In normal circumstances the ventilation current will be created by the traffic itself. The system will only operate in the case of a traffic jam or disaster.

Due to the compact method of tunnel construction there is usually very little space available for fixing ventilators so that one is forced to choose ventilators with a small diameter. To be nevertheless able to design a system with a reasonable total efficiency the boosters must have the largest possible impulse with the smallest possible diameter and power consumption. Capacity in this context means the product of the moved volume of air and the speed at which it flows from the booster. The volume of air is restricted by the permissible speed in the booster. If this is set too high, then the efficiency of the booster will decrease too much.

A second possibility of improving the efficiency of the ventilation system is by installing "deflection blades" in the air flow just behind the ventilator. Due to the fact that the boosters are fixed close to the wall and roof of the tunnel high friction losses arise due to the coanda effect. By deflecting the air flow this effect is counteracted resulting in an improvement in efficiency. In addition the air speed near the next ventilator can be lowered by installing deflection blades whereby the effective driving force increases.

For submerged tunnels the limited space available is the major problem in achieving reasonable efficiency. In mountain tunnels this problem of space does not arise because of the horseshoe-shape of the tunnel cross section (see Figure 5.11). In these tunnels larger ventilator diameters can be used so that a better output flow rate can be achieved at lower outlet speeds combined with larger quantities.

In submerged tunnels an obvious solution is to reserve more height above the clearance space profile thus also creating more space for the installation of other equipment, such as lighting, tv cameras, traffic signs, etc. The extra costs have up to now been considered too high. This aspect must be looked at again for the tunnels to be built in the future because the problem of damage to tunnel systems by vehicles which are too tall is taking on increasingly larger proportions.



Longitudional ventilation in mountain tunnels

For the time being the space in submerged tunnels will remain limited so that a ventilator is being sought which has the best properties for this specific application. The Civil Engineering Division of RWS in cooperation with the manufacturer has been successful in developing a reversible axial ventilator whose performance is 20% higher than that of the ventilators used up to now. The improved efficiency is shown by the specific propelling force for an external ventilator diameter of 750 mm which is increased to 34 N/kW, whereas 28 N/kW is usual for ventilators used up to now. Further research will be carried out for the future application of other ventilator diameters. It is expected that it is possible to improve the efficiency of ventilators with smaller and larger diameters.

5.4.2. Longitudinal ventilation with a closed injector

The most important characteristic of the system with an injector is that a certain volume of air is blown in from outside at high speed in the direction of the longitudinal axis of the tunnel tube. This system has been applied in the Coen tunnel and in the Benelux tunnel. Described briefly the system is as follows (see Figure 5.12). From the tunnel entrance there is an air supply duct at approximately 30 m into the tunnel which discharges into the tunnel tube at an angle of 5 to 20° through an opening in the ceiling. A large volume of air is blown in from outside through this opening at a speed of about 30 to 35 m/s. The mass of air combined with the difference in speed of the tunnel air and that of the blown in air forms the driving force on the air in the tunnel. This force must overcome the resistances of the tunnel tube, the input and output losses, the effect of wind, atmospheric pressure differences and the resistance of the traffic.



FIGUUR 5.12: Longitudional ventilation with an closed injector

Due to the relatively high speed at which air is blown in, areas of under pressure arise producing a considerable volume of air at the tunnel entrance. This sucked in air together with the air blown in by the injector forms the volume of air with which the tunnel is ventilated. The volume of air which is sucked in depends on the resistance in the tunnel. If the resistance encountered by the air blown in is too large, the air will flow outside to the tunnel entrance via the route with the least resistance. If the worst comes to the worst and the tunnel tube is totally closed, all the air blown in by the injector will escape from the tunnel entrance. This means that this system is limited in its applicability. If the resistance of the tunnel tube is too high, efficiency declines too much. This can be compensated by either increasing the capacity of the injector or by installing a second injector. This second injector must be installed at a good distance from the first one, otherwise effectivity will be adversely affected. The best position is where the air flow is evenly distributed over the whole of the tunnel cross section.

The installation of a second injector is difficult in most of the submerged tunnels in the Netherlands because this must be planned in the submerged part of the tunnel. Another method was therefore chosen for the Benelux tunnel in order to reduce the tunnel resistance. Back up boosters are installed in the submerged part of the tunnel just outside the headroom profile. This method is certainly less efficient because no air is supplied from the outside. In this way it is possible to ventilate an approximately 1000 m long tunnel. Resistance becomes too large in longer tunnels as a result of which the effectivity of the injector decreases too much.

If the injector operates with "fresh" outside air, the system is advantageous in the event of fire.

5.4.3 Longitudinal ventilation with an open injector

A variation of the injector system is operating in a tunnel in Denmark. In this tunnel the injector is placed at the beginning of the tunnel without an injector opening, thus making the construction simpler. The injector in this tunnel is formed by a slanting roof section at the beginning of the tunnel (see Figure 5.13).

The same applies to the system with an open injector as has already been stated under the section on longitudinal ventilation with a closed injector. The system is less efficient so that with larger tunnel resistances flow back of air will occur earlier than with the closed injector.



FIGURE 5.13: Longitudional ventilation with an open injector

This system clearly has civil engineering advantages due to its simplicity. By now combining the open injector with the booster system distributed over the length of the tunnel a simple system can be constructed which has the advantages of simplicity combined with safety in the event of fire.

5.4.4 Longitudinal ventilation with an open injector combined with boosters distributed over the length of the tunnel

The boosters, distributed over the length of the tunnel, lower the resistance of the system so that the open injector can operate reasonably

efficiently. Experience has been gained with this combined system in the Benelux tunnel. Although

the system installed in this tunnel is a closed injector system it is expected, also based on experience with this system in the Guldborgsund tunnel, that good results can also be obtained with an open injector in combination with boosters distributed over the length of the tunnel. (See Figure 5.14).



FIGURE 5.14:

Longitudinal ventilation with an open injector, combined with boosters distributed over the tunnel length

As already mentioned in this chapter and elsewhere, the installation of boosters at the beginning of the tunnel near the entrance has advantages in the event of fire. The boosters in the open injector must be installed in such a way that sucking in of outside air is guaranteed. Only if the fire occurs right under the boosters will they break down but then the boosters distributed over the length of the tunnel will remain in operation by switching them over to operating in the reverse direction.

5.5. AIR POLLUTION AND VENTILATION SYSTEMS

The development of air pollution and the air speed over the length of the tunnel can be represented graphically for the three basic ventilation systems described: transverse ventilation, semi-transverse ventilation and longitudinal ventilation. See Figures 5.15 to 5.17. Data taken from [2] is used at the basis for this, in which it is given diagrammatically in which way the air speed and the concentration of dangerous substances are connected to the method of ventilation. It is presumed here that :

- a stationary situation has been established
- the mixing of the dangerous substances with the air in the tunnel is complete and is homogeneous over the cross section
- the quantities of air blown in and extracted by the transverse and semi-transverse ventilation systems as well as the production of dangerous substances are constant in the longitudinal direction of the tunnel.

In Figures 5.15 to 5.17:	
Q_t = air flow rate in the tunnel tube	(m^3/s)
u^t = average air speed in the tunnel tube	(m/s)
A^{t} = surface area of cross section of tunnel tube	(m ²)
L = length of tunnel tube(m)	
q^i = volume of fresh air blown in per m tunnel length and per m ² cross section	(s ⁻¹)
q^{a} = volume of fresh air sucked in per m tunnel length and per m ² cross section	(s ⁻¹)
a = volume of dangerous substances produced per m^2 cross section	(g/m ³ .s)
C = concentration of dangerous substances	(g/m^3)

The concentrations can be derived from theoretical considerations which are summarized in 5.5.1. to 5.5.3.

5.5.1. Transverse ventilation

In transverse ventilation the development of the concentration (C) over the length of the tunnel is constant if the longitudinal speed (u) of the tunnel air is 0 m/s (see Figure 5.15). At a certain positive longitudinal speed of the tunnel air the concentration at the beginning of the tunnel is 0 and reaches a maximum towards the tunnel exit.



FIGURE 5.15: Concentration of dangerous substances with transverse ventilation

5.5.2 Semi-transverse ventilation

If there is no longitudinal current, the speed of the tunnel air in the middle of the tunnel will be zero and will increase towards both ends of the tunnel to a maximum (see Figure 5.16).

The concentration of dangerous substances is constant over the whole length of the tunnel.

A longitudinal current is created by wind and/or the effect of traffic. Depending on the extent of this longitudinal current the zero point of the air speed shifts against the direction of the longitudinal current until outside the tunnel. The concentration of dangerous substances is constant over the whole length of the tunnel as long as the longitudinal speed of the tunnel air is lower than or equal to the exit speed as a result of the air supplied without the effects of wind and/or traffic. If this longitudinal speed increases, the concentration will rise from 0 to a maximum, as shown in the figure.





5.5.3 Longitudinal ventilation

Although small differences exist between the different longitudinal ventilation systems this aspect will not be dealt with here in detail. This section will be confined to giving an indication of the development of the concentration as a function of air speed for the booster system, which is combined with an open injector (see Figure 5.17). Longitudinal ventilation with boosters combined with an open injector is characterized by a constant increase in the concentration with the length of the tunnel. The maximum concentration is reached at the tunnel exit. The magnitude of the maximum depends on emission of pollutants and the speed of the tunnel air in the longitudinal direction. If the air speed decreases and emission remains the same the concentration will increase towards the end of the tunnel. At higher air speeds the reverse applies.





5.6.1 General

Several facets of the ventilation systems and fire are described in this section. The relevant information for the ventilation system concerned will be dealt with in this section.

5.6.2 Transverse ventilation

As already noted the longitudinal current can be difficult to control with transverse ventilation. Since this can lead to very dangerous situations in the event of fire, a supplementary system must take care of the control or guiding of the longitudinal ventilation current. This can be for example by installing several reversible boosters or by the use of an injector at both ends of the tunnel. Whichever supplementary system is chosen it must be reversible.

In tunnel tubes with one-way traffic extracting a proportion of the combustion gases via the tunnel tube can be considered. This is possible if the traffic can leave the tunnel tube downstream from the fire. This ventilation possibility cannot be implemented if there is a traffic jam on the road surface after the tunnel and this also leads to a blockage in the tunnel.

In the event of an accident in the counter flow of traffic in which a fire breaks out, an exceptionally dangerous situation arises. If a possible longitudinal current is created, the traffic downstream from the fire will be exposed to smoke and hot combustion gases with the danger arising of being suffocated or burned. By providing the transverse ventilation system with a supplementary system, which controls the longitudinal current, the combustion gases are concentrated at the site of the fire. The supplementary system can be realized by for example using reversible boosters. If there is no space available for this, an injector installed at both ends of the tunnel could achieve the same aim.

For tunnels with two-way traffic the transverse ventilation system of a sufficient capacity perhaps offers a safer solution, if attention is also paid to controlling the longitudinal current. Since the flow of traffic is blocked before as well as after the site of the accident the ventilation system must extract as much as possible of the hot combustion gases from the site of the accident. This means it is necessary that valves are fitted in the exhaust duct which can be opened for example on the basis of temperature or electromechanically. In addition air will be supplied to the adjacent sections to prevent movement of the hot combustion gases as much as possible.

From calculations it is evident that the supply of fresh air is not a decisive factor but the extraction of the combustion gases is. The exhaust ducts must have a cross section which is roughly five times larger than that of the supply ducts. The civil engineering consequences of all this are considerable but are not important for tunnels in the Netherlands because the tunnels are short and two-way traffic is not normally permitted. The fact remains, however, that from the safety point of view transverse ventilation, if correctly designed, offers a safe solution in the event of fire. The costs are, however, considerable, certainly for longer tunnels. The chance of the occurrence of fire must be weighed up probabilistically against the extra costs involved of such a solution.

5.6.3 Semi-transverse ventilation

It was shown from tests carried out several years ago in the Coen tunnel on the system described in Figure 5.6 that the supply of fresh air in the case of fire resulted in the mixing of the smoke. Increasing the capacity had a negative effect on this phenomenon so that this system is decidedly unsuitable to be able to function properly in the event of fire. Perhaps better results would be obtained, if extraction took place from the top of the tunnel tube. No experience has been had of this method in the Netherlands.

As already stated in section 5.3 the semi-transverse ventilation is also unable to control the longitudinal current. Therefore attention must also be given to controlling the longitudinal current in this system.

5.6.4 Longitudinal ventilation

Fire can start in the tunnel as the consequence of an accident. There is an important difference in approach to a fire in a tunnel tube with one-way traffic and that in a tunnel tube with two-way traffic. A extremely dangerous situation is created, if fire occurs as the result of an accident in the counter traffic. Due to the presence of the longitudinal current the traffic downstream from the fire is exposed to smoke and hot combustion gases with the danger of suffocation or burning. It is therefore certainly unadvisable to use longitudinal ventilation in tunnels with two-way traffic in the normal operating situation or in very long tunnels.

In a system with boosters one must decide how

many boosters will remain in operation during emergency assistance. This consideration is necessary because it is not possible to make ventilators which can resist high temperatures in the area downstream from the fire.

By installing a closed injector, which uses outside air, it will in all probability remain in operation during the fire due to the supply of outside air. It therefore applies as a condition that such provisions have already been made during construction that no damage to the ventilators can occur, if the fire takes place right under the injector. The ventilators required for this system are not exposed to high temperatures and cannot therefore break down due to the fire. In view of the high risk of boosters installed in the tunnel breaking down the system with closed injector can be an advantage with respect to boosters distributed over the length of the tunnel.

As already noted earlier in this chapter and also elsewhere, there are advantages in the event of fire in placing the boosters at the beginning of the tunnel near the entrance. By putting as much as possible of the ventilation capacity at the beginning of the tunnel, the number of ventilators situated after the fire is restricted. If there is enough space available in the transverse profile, several groups of boosters fitted on the ceiling can provide a substantial capacity. There is, however, a limit to the centre-tocentre distance between these groups. If there is no space available in the transverse profile, then the open injector at the beginning of the tunnel can provide the required capacity.

In an open injector system it is impossible to protect the ventilators installed in the injector against fire. This means that in the event of fire right under the open injector the system will fail. The open injector cannot be installed just like that, at any rate if a safe solution is being sought. Therefore a solution is being sought by combining two systems, namely an open injector in combination with boosters distributed along the length of the tunnel.

The boosters must be installed in such a way that drawing in outside air is ensured. Only if the fire occurs right under the injector, will it break down but in that case the boosters distributed along the length of the tunnel will remain in operation by putting them into the reverse way of operating.

By applying a **combined** system the chance of the ventilators breaking down is smaller than in the

simpler systems, as explained below.

If a "large" fire breaks out in the tunnel, all the ventilators 300 to 500 m downstream from the fire will break down. The prevailing temperature of the fumes in this area is higher than 250 to 300°C, to which the ventilators are not resistant. The other boosters further downstream in the tunnel remain operating, albeit at a reduced capacity, due to the lower density of the fumes. The open injector operates undisturbed and supplies the full capacity because "fresh" outside air is supplied.

If the fire is right under the open injector, the boosters installed there will break down and the direction of the ventilation should be reversed. This is possible because in this case the fire occurs almost outside the enclosed part of the tunnel and the traffic jam is at a standstill under the ventilation grid or in the open air. Reversing the direction of ventilation is necessary to obtain a booster capacity which is as large as possible in the closed part of the tunnel. See the next section 5.6.5 "Direction of ventilation in longitudinal ventilation".

5.6.5 Direction of ventilation in longitudinal ventilation

In by far the most cases a fire occurs because of an accident. As a result of which the traffic coming up from behind is blocked, while the traffic downstream from the fire is able to leave the tunnel normally. This means that at all times the smoke and the hot combustion gases are discharged in the direction of the empty tunnel tube. The situation that traffic behind the site of the accident is not able to leave the tunnel as quickly as possible due to a traffic jam or stagnating traffic must be prevented. In most cases it is possible to prevent this situation from arising by using a traffic detection system by which the traffic is controlled in good time *in front of* the tunnel tube. In this way the risk of possible casual-ties is minimized.

This approach assumes that a great deal of damage will be done to the interior of the tunnel downstream from the site of the fire due to high temperatures and smoke. This is considered acceptable because material damage is considerably more preferable to non-material damage.

It is conceivable that the fire occurs at the entrance of the tunnel, several metres into the tunnel. The traffic will then be under the sun-excluding grid or just outside the tunnel. In order to limit material damage in such a situation the direction of ventilation must be reversed. This reversal will have to be carried out manually because an assessment of the situation locally is indispensable before reversing the direction of ventilation.

A second reason for making the ventilation system reversible concerns the number of ventilators which break down because of the high temperatures. It is assumed that in the case of a "large" fire a large proportion of the equipment downstream from the site of the fire will not function properly any more after some time. Refer to 2.5.8 "Reversible longitudinal ventilation system".

Since the extent of the damage to the interior of the tunnel largely depends on the direction of ventilation chosen and that this decision is taken by the control room staff under difficult circumstances, an unambiguous instruction is necessary. This is provide for by a contingency plan.

A third reason for making the ventilation system reversible is described in section 5.7.

5.7 AERODYNAMIC SHORT-CIRCUITING

By short-circuit currents is meant all air currents of polluted air from the tunnel tube or the ventilation outlet opening which are totally or partially extracted due to the supply of fresh air. The wind speed and the wind direction play an important role here. If 10% of the air flow rate supplied arises from shortcircuit currents, approximately 11% more fresh air is required to ventilate the tunnel with the same degree of pollution. Energy consumption thereby increases by approximately 37%. The extra amount of air must be able to be realized with the existing ventilation system. If sufficient ventilation capacity is available, short-circuit currents of 10% or less have no effect on safety and comfort in the tunnel.

The situation is otherwise in the case of fire. Car fires in road tunnels often produce a tremendous amount of smoke. Visibility in the tunnel, where the fire rages, decreases in the smoke zone to 10 to 15 cm. With a short-circuit current of 10%, as a consequence which visibility in the fresh air current is 1.5 m which is unacceptable. In addition the short-circuit current causes a sharp decline in the quality of the fresh air to such an extent that the danger of suffocation arises. In transverse ventilation systems short-circuit currents can be almost totally prevented by the installation of a polluted air flue or shaft. This also applies to the semi-transverse ventilation system, provided that this system is reversible in the event of fire and that the smoke at the site of the fire can be extracted resulting in fresh air flowing in from the entrance or exit. In longitudinal ventilation systems short-circuit currents can be almost totally prevented by installing an exhaust shaft with flues at the end of the tunnel tube where the polluted air leaves the tunnel. Such shafts with flues are often constructed in the first instance for the so-called "environmental extraction" (see Chapter 12).

In longitudinal ventilation additional attention must be paid to measures to prevent short circuiting. Research carried out by the NLR on aerodynamic short circuiting in the Botlek tunnel showed that structural provisions in the form of smoke walls, extended exits, etc., are not always effective. With certain wind directions these aerodynamic short circuits will arise in spite of the presence of structural provisions. It is therefore proposed that by choosing the right course of action for ventilation these aerodynamic short circuits in the case of fire are prevented.

In longitudinal ventilation by means of boosters polluted air and smoke during a fire can be prevented from flowing into the clean tunnel tube by way of short-circuit currents. By reversing the direction of ventilation in the "clean" tunnel tube the direction of flow in both tunnel tubes will be the same, so that the out-flowing smoke cannot be sucked in by the ventilation system of the "clean" tunnel tube. Both tunnel tubes will then suck in or blow out air on the same side. The capacity of the boosters must be sufficient to create a ventilation flow in the opposite direction also in the event of a head wind. The boosters must be put into reverse for this. The fire brigade will be able to fight the fire from the clean tunnel tube through the so-called dividing doors. If the ventilation speed in the clean tunnel tube is lower than the ventilation speed in the tunnel tube where the fire rages, a pressure difference will arise as a result of which the smoke will not flow in the direction of the clean tunnel tube when the dividing doors are opened.

If longitudinal ventilation is realized by means of a closed injector it is possible that the "clean" tunnel tube is kept under pressure by air from the injector. By fixing a special fire valve in the injection jet the air distribution can be controlled in such a way that clean air leaves this tunnel tube through the exit as well as the entrance so that short circuit currents cannot arise and the adjacent tunnel tube remains free of smoke.

This is based on the fact that the air extracted by the injector is free of smoke due to the installation of for example a flue.

If longitudinal ventilation is realized by means of an open injector, then extraction cannot be smokeless so that this system as well as the above-mentioned system with boosters distributed along the length of the tunnel must be reversible. For this purpose the tunnel can be supplied with open injectors at both tunnel openings or a combined system can provide the solution.

6 PERMISSIBLE LEVELS OF AIR POL-LUTION

(W.A.M. den Tonkelaar)

6.1 GENERAL

Information is provided in this chapter about the dangerous substances emitted by road traffic and their effect on the health of human beings. It has been shown to be impossible to refer to existing standards for all the situations arising in a tunnel. Therefore a selection must be made of the various permissible values based on the information supplied.

In Chapter 9 the permissible value for carbon monoxide (CO) is determined on the basis of among other things the data reported in this chapter. The other dangerous substances reported in this chapter cannot be calculated by the probabilistic method yet. It is intended to make the calculation method suitable for this in the future. As stated in the conclusion of this chapter, carbon monoxide is still the normative substance at the moment, therefore it was decided to work out the probabilistic method for this substance.

Alongside industry, energy generation and the agricultural sector, motorized road traffic is the most important source of air pollution in the Netherlands. Although air pollution from road traffic is apparent in the whole country, it is especially a problem in the densely populated centres and alongside busy traffic routes. This means that a large variety of compounds are involved which are emitted near ground level, therefore directly into the area where we live. Measurements indicate that the highest concentrations are found in road tunnels. This is the consequence of the usually high density of vehicles combined with a limited dilution of exhaust fumes.

The following substances emitted by road traffic are being taken into consideration for an assessment of the health risks. Nitrogen oxides (NO_x) and hydro-carbons (CO) account for the most dangerous substances:

- nitrogen dioxide (NO_2)
- carbon monoxide (CO)
- benzene (C_6H_6)
- benzapyrene (BaP)
- sulphur dioxide (SO_2)
- lead
- soot
- ozone

A motorist usually only spends a short time in a tunnel. At a speed of for example 60 km/h and a tunnel 1,000 m long, the time spent in the tunnel is only 1 minute. The health risks of such a short exposure cannot be specified but they will be small compared to the risks people run from the inhalation of dangerous substances during normal driving. The risks to free-flowing traffic in a tunnel are not taken into consideration but those of the motorist in stagnating traffic are. It must be remembered in this respect that traffic jams and stagnating traffic often occur in the vicinity of tunnels and especially on roads leading up to the tunnel and not usually in the tunnel itself (Coen tunnel, Velser tunnel, Benelux tunnel). The following situations can be distinguished for the assessment of the quality of the air:

- 1. Motorist in stagnating traffic
- 2. Member of emergency service (personnel) who must carry out work for a short time in connection with a traffic jam or an accident
- 3. Motorist who after a disaster must escape from the tunnel
- 4. Pedestrian areas in the immediate vicinity of the tunnel

Other situations, such as fire in the tunnel, are not considered because there are no health standards for these incidental situations.

There are two types of statutory standards for the quality of air in the Netherlands, namely limiting values for the quality of outside air and maximum acceptable concentrations for working conditions (MAC values). These MAC values, at least 15minute values, are applicable to situation 2. The limiting values for the quality of outside air are intended for pedestrians in public pedestrian areas (situation 4) but do not apply to motorists nor in tunnels. A road tunnel is a prohibited area for pedestrians. Motorists escaping on foot (situation 3) can be considered to be pedestrians. The limiting values are, however, not intended for such extreme circumstances or short periods. The limiting values for the quality of outside air are likewise not applicable to the situation of stagnating traffic in a tunnel (situation 1).

In conclusion the statutory limiting values exist for situations 2 and 4. For situations 1 and 3 limiting values will be deduced from partially supplementary data.

6.2 HEALTH ASPECTS OF AIR POLLUTION

Two effects of air pollution can be distinguished; acute toxicity an effect which occurs within a certain time period as the result of a short exposure and chronic toxicity (including carcinogenity) resulting from long exposure to relatively low concentrations. It is usually difficult to find a direct connection between the concentrations and the effects on human beings. The causes of illnesses are very complex and there are often more factors involved. Information about the action of low concentrations of polluting substances on human beings is very sparse. Since exhaust fumes contain a large number of compounds the effects are often nonspecific (cannot be traced back to a single substance) and some substances reinforce or weaken each others actions, no general epidemiological research on the specific action of exhaust fumes on human beings is known. Research has been carried out on the separate substances.

The main effects on the health of human beings are:

- NO₂ : increases respiratory resistance, chronic bronchitis, loss of lung elasticity and decrease in resistance against infections of the lung tissue.
- CO : impedes the uptake of oxygen in the blood by combining with haemoglobin.
- C₆H₆ : plays a role in causing leukaemia, while at high concentrations chromosome mutations can occur, is carcinogenic.
- BaP : is carcinogenic, causes the formation of lung tumours. It is considered to be representative of the polycyclic aromatic hydrocarbons (PAH).
- SO₂ : irritates the mucosa, adversely affects the cleansing capacity of the respiratory tracts.
- Lead : slows down the production of haemoglobin, can cause damage to the kidneys and the central nervous system, can result in brain damage in young children, can cause damage to the nervous system and the production of blood in the unborn child.

- Soot : reinforces the effects of SO_2 , adversely affects the lungs.
- Ozone : decreases respiratory function associated with infection reactions, hyperactivity and alteration of lung clearance, increases the frequency and seriousness of complaints in people with existing heart and respiratory complaints, symptoms such as irritations of the eye, nose and throat, coughing, pain in the chest, shortness of breath, headache, nausea and dizziness. After an episode of increased ozone concentration (summer smog) complete recovery may occur. In repeated exposure permanent changes in lung function must in principle be taken into account.

6.3 DUTCH LIMITING VALUES FOR THE QUALITY OF OUTSIDE AIR

Objectives for the quality of the air have been formulated to protect people and the environment. Limiting values, directive values and target values are distinguished. Limiting values may not be exceeded now or in the future. The directive values are more stringent and involve quality objectives which are considered attainable within a certain period of time. In the course of time the directive values will be accentuated to eventually reach the target values. Target values in contrast to limiting and directive values have no legal basis. The risks below these target values are considered to be negligible.

The limiting values of components which can cause damage at high concentrations for a short period of time are based on the counteraction of such situations. The percentile value of 98 is taken as the limit, which means that the concentration level may be exceeded only 2% of the time.

A summary of the limiting values for air quality, taken from Substances and Standards 1990, is given in Table 6.1.

TABLE 6.1:Limiting values for air quality

substance	limiting value ^{1) 2)} $(\mu g/m^3)$	status	description ³⁾
NO ₂	135	limiting value	98-percentile of values per hour
	80	directive value	98-percentile of values per hour
	175	limiting value	99,5-percentile of values per hour
	300	limiting value	average per hour
со	6.000	limiting value	98 percentile of 8-hour value
	40.000	limiting value	99,99 percentile of values per hour
C ₆ H ₆	10	limiting value	average annual concentration
BaP	0,005	limiting value	average annual concentration
	0,0005	directive value	average annual concentration
SO ₂	75	limiting value	50 percentile of 24-hour value
	250	limiting value	98 percentile of 24-hour value
	30	directive value	50 percentile of 24-hour value
	100	directive value	98 percentile of 24-hour value
	830	limiting value	average per hour
Lead	2	limiting value	98 percentile of values per hour
	0,5	limiting value	average annual concentration
Soot (black smoke)	30 75 90 150	limiting value limiting value limiting value limiting value	50 percentile of 24-hour value 95 percentile of 24-hour value 98 percentile of 24-hour value 24-average per hour
Ozone	240 120	limiting value (design) target value	average concentration per hour (may be exceeded a maximum of 5 days /year) average per hour

1) $1 \mu g = 0.001 \text{ mg}$

2) For conversion to other units refer to "Conversion factors"

3) The 50, 95 or 98 percentile value means that the average concentrations per hour, per 8 hours or per 24 hours are not exceeded for 50, 95 or 98% of the year.

Because fine particles and SO_2 reinforce each others' action a combined limiting value will be used in view of the occurrence of periods of winter smog.

6.4 MAC VALUES FOR HEALTH AND SAFETY AT WORK

The Health and Safety Inspectorate has formulated MAC values in the form of Maximum Acceptable Concentrations – Time Weighted Averages (MAC-TGG) for health and safety at work. Time Weighted

Averages are understood here to mean the maximum acceptable concentration for an exposure lasting up to 8 hours a day and not more than 40 hours a week. Time weighted averages allow concentrations to be exceeded for short periods, assuming, however, that the time weighted average is not exceeded in the working day.

A limiting value of short duration (time weighted average lasting for 15 minutes) has been adopted for several substances. For those substances for which no 15-minute MAC-TGG has been determined (yet), including all traffic pollutants stated in this publication, a coefficient of 2 is being temporarily used by the Health and Safety Inspectorate as a guideline with respect to exceeding the 8-hour MAC-TGG for a short time.

A summary of the MAC values is given in Table 6.2.

TABLE 6.2:

MAC values of substances emitted by traffic.

substance	MAC-TGG 8 hour (µg/m3)
NO2	2.000
со	29.000
С6н6	30.000
Bap *)	10
SO2	5,000
Lead	150
Dust, inhaleable	5.000
Ozone	200

*) Derived value (5% of the coal tar dissolvable in benzene).

The values given above only apply to (healthy) employees and are used for industrial areas. With the exception of the value for CO, the MAC values are much higher than the limiting values for the quality of outside air. They should not be applied to all sections of the population (this means to children, ill people and older people) and for exposure lasting for twenty-four hours a day.

6.5 OTHER AIR STANDARDS

Besides the statutory Dutch limiting values for air quality and the MAC values there are the following standards for air quality:

- World Health Organization (WHO) standards
- European Community (EC) standards
- values proposed in the standard documents on benzene and fine dust
- new standards to prevent winter smog.

Several additional standards are given in Table 6.3 based on a short time of exposure to substances emitted by traffic.

 TABLE 6.3:

 Additional standards for air quality

substance	limiting value 1) (µg/m3)	duration	description
NO2	400	1 hour	WHO Air Quality Guideline [3]
со	100.000	15 min.	WHO Air Quality Guideline [3]
C6H6	30-1000	1 hour	Standard document benzene (under discussion)
SO2	350	1 hour	WHO Air Quality Guideline [3]
Fine dust	140	24 hour	Standard document fine dust
Fine dust	350	1 hour	Winter smog standard
+ SO2			stage 1
	450	1 hour	ditto stage 2
	700-1300	1 hour	ditto stage 3

1) Refer to "Conversion factors" for conversion into other units.

6.6 AIR QUALITY REQUIREMENTS IN AND AROUND TUNNELS

On the basis of the existing standards for traffic pollutants the following requirements can be formulated for the situations mentioned in 6.1 (see Table 6.4). The values given in the table are 98 percentile values which may be exceeded 2% of the time.

The effects of air pollution depend on the exposure time. Although these effects do not increase linearly with exposure (exposure time x concentration) in all cases, it roughly applies that at shorter exposures than those given in Table 6.4, the air quality requirements can be proportionately less strict.

TABLE 6.4:

Air quality requirements in and around road tunnels for four situations with different exposure times (concentrations in μ/m_3).

substance	short exposure not shorter then 15 min. or longer then 1 hour				long exposure		
	situation 1 stagnating traffic	situation 2 accident	situation 3 emergency services	situation 4 environment			
NO.	300	4 000	400	135	(98-n)		
CO	40.000	58.000	100.000	6.000	(98-p)		
C _c H _c	300	60.000	1.000	10			
BaP	-	20	_	0,005			
SO ₂	350	10.000	830	250	(98-p)		
Soot	-	_	_	90	(98-p)		
Fine dust	_	10.000	– .	see	soot		
Fine dust $+$ SO ₂	450	-	1.000	350			
Lead	-	300	_	2	(98-p)		
Ozone	_	400	_	240			

- no standard for short exposure.

Although Table 6.4 does not give any permissible values for soot (particles) these are actually important in connection with the deterioration in visibility. These values are not given here because soot does not result in increased health risks at short exposures. A permissible value is given for the environment, therefore at longer exposures. The acceptable quantity of soot (particles) in the tunnel air is dealt with in Chapters 3 and 9.

In Chapter 10 May's graph is used for the absorption of CO in the blood thus making it possible to determine the absorption of CO in the blood also with a very short exposure. See also Appendix A.

6.7 DISCUSSION AND CONCLUSIONS

In the assessment of the health risks the strictest standards must be used in the vicinity of residential and pedestrian areas (long exposure). The opposite applies to emergency and service personnel. Stagnating traffic in a tunnel occurs more often than a disaster in which the motorists must escape from the tunnel. Higher requirements must therefore be set on the air quality in the event of stagnating traffic.

Situation 1

In situation 1 (stagnating traffic in the tunnel) the emission of CO, unburnt hydrocarbons and soot will increase substantially compared to that of fast-flowing traffic. NO_x , SO_2 and lead will decrease. Due to the reduced ventilation in this situation the concentrations will increase even more strongly or just increase. The ozone in the outside air will nearly completely disappear in the tunnel by reacting with the NO in the exhaust fumes (95% of the NO_x emission). The volume of NO_2 in the tunnel is also limited because the conversion from NO and ozone is limited. In addition to ozone and NO_2 the limiting value for SO_2 will also not be exceeded very quickly because of the relatively low emission by the road traffic.

A comparison of the possibly occurring concentrations with the limiting values shows that in the stagnating traffic situation CO is the most critical component for a short exposure.

Situation 2

For emergency and service personnel who have to enter the tunnel in the case of stagnating traffic or a disaster, the limiting values are at a much higher level. It also applies here, however, except in the event of fire, that CO will be the first limiting value to be exceeded. This is due to the fact that, in contrast to the other substances, this substance has effects even at short exposures.

Situation 3

Situation 3, escaping motorist (drivers and passengers who leave the tunnel on foot in the case of a disaster) is similar to situation 1. If the engines are turned off by the majority of motorists, the concentrations will not increase so much. However, the total exposure can increase due to the larger respiratory volume involved in the effort to leave the tunnel. CO is the determining component here also. If as a result of the disaster, petrol is released (accident with a tanker or a leaking petrol tank) the concentration of benzene can become a determinative factor. The danger of fire is, however, the most threatening factor in this situation (smoke production, lack of oxygen). The same applies to an accident in which LPG is involved.

Situation 4

The exhaust fumes produced in a tunnel are released into the environment in a concentrated form, either at the ends of the tunnel or from the outlet point of the extraction system. In a tunnel ventilated naturally the moving vehicles ensure that there is a substantial ventilation flow, which for each tunnel tube results in the exhaust fumes being transported to the end of the tunnel. The concentrations will be higher mainly in the immediate surroundings of the ends of the tunnel. The levels of air pollution in this situation depend on the intensity of the traffic, the proportion of goods traffic, the length of the tunnel and the background concentrations in the area where the tunnel is located (high in the case of the Benelux tunnel).

The limiting value for NO₂ expressed as the 98 percentile for values per hour of $135 \ \mu g/m^3$ must be considered first when looking at exceeding the limiting values. A clean-up value of $160 \ \mu g/m^3$ applies temporarily to existing situations within the built-up area. These values are exceeded in several very busy traffic situations in the Netherlands. The contribution made by tunnels will only be important in pedestrian areas in the immediate vicinity of the tunnel openings. Due to the shape of the tunnel openings, which can be shaped in such a way that extra turbulence is created, the effect of tunnel emissions can be reduced.

6.8 FINAL CONCLUSIONS

The following conclusions can be made from the above:

- CO is the most dangerous substance for motorists, emergency and service personnel in the tunnel. The permitted concentrations for these groups of people lie at approximately the same level. Constant recording of the substances is necessary. Problems can be prevented by the automatic switching on of additional ventilation on approaching or exceeding a certain concentration, for example at 40 mg/m³ (40,000µg/m³).
- when a tunnel is constructed attention must be paid to stopping the heavily polluted air released from a tunnel from being sucked in or blown into the other half of the road tunnel by the traffic. This can be prevented by installing so-called smoke walls or by extending the exits of the tunnel further than where the entrance begins.
- for surrounding residential and pedestrian areas NO₂ is the most critical substance. Exceeding the limiting value will, however, mainly be the consequence of the background concentration already prevailing without the tunnel.
- the effect of tunnels on the environment can be reduced by the shape of the ends of the tunnel (grids or awnings). In special cases it can be necessary to install a ventilation system which prevents polluted air from being released in the vicinity of residential areas. Examples of this have already been built in other countries, such as in St. Gallon in Switzerland.

7 CALCULATION METHOD FOR LON-GITUDINAL VENTILATION SYS-TEMS (P.F. Hartman, N.P. Costeris, L. Swart)

7.1 GENERAL

In view of the fact that mainly tunnels with longitudinal ventilation systems will be built over the coming years in the Netherlands, only this system will be dealt with in this chapter.

This chapter provides the basic information to make a ventilation calculation for a road tunnel.

The driving force necessary for longitudinal ventilation can be supplied by boosters as well as by an injector, therefore the calculation method is given for both systems. It is also possible to start with a combined system. The calculation method is given for this too.

The total driving force is the sum of the separate driving forces of all the boosters present (and operating) or in the case of an injector system, the sum of the driving forces supplied by the injectors. This must be large enough to overcome all the resistances arising in the worst situation which are encountered by the air flow.

This chapter deals consecutively with the following subjects which are relevant to the calculation:

- the driving force of the booster
- the driving force of the injector in an open or closed design
- the resistance of the empty tunnel
- the inflow and outflow losses
- the effect of traffic
- the effect of wind
- the fall in pressure over the source of the fire.

7.2 DRIVING FORCE OF THE BOOSTER

The boosters with their injection method of operating must supply the required driving force. In addition to the booster system the traffic and the wind can in some cases also make a positive contribution to the total driving force available. If the speed of the traffic is greater than the speed of the air flow in the tunnel and if the wind creates a positive pressure difference over the entrance and exit openings, a driving force arises. In the calculations a negative vehicle resistance/wind effect is therefore assumed.

7.2.1 Theoretical maximum driving force

The driving force of the booster can be calculated as follows:

$$I_a = \rho x u_a x Q_a \tag{7.1}$$

where:

I,	=	driving force of the booster	(N)
ρ	=	density of the air	(kg/m^3)

u = average air speed in the outflow opening of the booster (m/s)

 $Q_{1} = air flow rate of the booster (m³/s)$

Output and outflow rates are features of the booster which are a function of the size and type of booster. These features are specified by the manufacturer and must be determined according to the measuring method described in Chapter 12.

7.2.2 Theoretical actual driving force

The driving force calculated in (7.1) is a purely theoretical value. The actual value is lower due to losses in the outflow opening due to rotation and turbulence which cannot be calculated exactly but amount to approximately 3 to 7% of the theoretical driving force.

The equation for the actual impulse can be written as follows:

$$I_a = \rho x ua x Q_a x \eta_a$$
(7.2)

where:

 η_{1} = impulse yield of the booster.

The impulse yield is the quotient of the actual driving force measured in an unrestricted area in which the ambient air speed is 0 m/s and the calculated driving force is calculated according to (7.1).

7.2.3 Actual effective driving force in the tunnel tube

To be able to determine the actual effective driving force of a booster the following factors should be taken into account:

- the air speed in the tunnel tube
- the positional efficiency
- the modified impulse yield as a result of the circulating surrounding air.

Air speed in the tunnel

The booster transmits its total driving force to the tunnel air flow, if the outflow speed is reduced to the ambient air speed. Since the tunnel air flow always has a certain speed, the value measured in the laboratory can never be reached and a lower driving force must be used in the calculations. The driving force which can be transmitted depends on the difference between the outflow speed and the air flow speed in the *empty* tunnel as follows:

$$\mathbf{I}_{empty} = \rho \mathbf{x} (\mathbf{u}_{a} - \mathbf{u}_{b}) \mathbf{x} \mathbf{Q}_{a} \mathbf{x} \eta \mathbf{a}$$
(7.3)

where:

u_t = average air speed in the *empty* tunnel tube (m/s)

In a tunnel tube full of *traffic* the driving force which can be transmitted is:

$$I_{\text{traffic}} = \rho x (u_a - u_{\text{eff}}) x Q_a x \eta a \qquad (7.4)$$

where:

u _{eff}	=	air	speed	in	the	tunnel	tube	full	of
		traf	fic					(m	I/S)

Positional efficiency

The boosters create a "jet flow" which flows along the tunnel walls and/or ceiling at high speed. The losses which occur due to friction are allowed for in the positional efficiency of the booster. This output efficiency mainly depends on the distance of the booster from the side wall and the ceiling.

It is often a problem for the designer that the circumstances applying to his design are not described in the various publications or model tests. Therefore the choice of the positional efficiency requires a certain amount of experience. To give a few guidelines for this the following background information is supplied on the different parameters and their effect on positional efficiency:

- There is a connection between the surface area of the outflow opening of the booster and the surface area of the cross section of the tunnel tube. The smallest losses occur in tunnels with a large cross section, as is often the case in mountain tunnels (horseshoe) and with a relatively small booster cross section, placed in the centre of the cross section. A positional efficiency of ≈ 1.00 is then possible, if the boosters are installed at a large distance from each other. This arrangement is not feasible because of problems with the traffic. If the boosters are placed at the side of a tunnel tube of a submerged tunnel this positional output, with a large distance between the boosters, is in the region of 0.55 to 0.65.
- Fixing deflection blades immediately after the outflow opening can increase this output rate by 10 to 15%. If due to fitting deflection blades the air current does not touch the wall in the area where the speed is still high, frictional loss decreases. The speed of the air blown out is high near the outlet opening of the ventilator and because frictional losses increase as a function of the square of the speed the greatest gains can be realized close to the booster.
- The additional resistance created by the deflection blades must not of course be too large resulting in a smaller driving force being available. It is thus a matter of finding a correct balance between the extra resistance created by the deflection blades and the reduction of frictional losses to be attained on the outflow side. A suitable deflection blade put at a correct angle results in an improvement in the positional efficiency. If the angle of deflection is too large then the extra resistance introduced will result in a decrease in the positional efficiency.
- By installing the boosters after each other in the longitudinal direction care must be taken that the boosters do not affect each other. If the outflow speed of the booster is not reduced equally over the whole of the cross section of the tunnel tube to the same speed as that of the tunnel air, the air speed at the inlet opening of the next booster can be higher than the average speed of the tunnel air. This unequal speed

distribution is an important cause of a low positional efficiency. This effect can also be improved by fitting deflection blades. The *minimum* centre-to-centre distance of the boosters without deflection blades is related to the outlet speed and is approximately 1.5 x u, m.

If deflection blades are fitted, the *minimum* distance is $0.5 \times u_a m$.

- If the distance between the ventilators is smaller, the positional efficiency decreases very sharply. The above-mentioned values are not absolute and are only given as an indication.
- The positional efficiency furthermore depends on the number of boosters that are mounted next to each other in a cross section. The output of a group of boosters, installed in one cross section is higher than the individual output, since this group may then be considered to be one booster with a larger outlet opening.

The equation for the determination of the driving force available per booster in an *empty* tunnel tube is therefore:

$$\mathbf{I}_{empty} = \rho \mathbf{x} (\mathbf{u}_{a} - \mathbf{u}_{b}) \mathbf{x} \mathbf{Q}_{a} \mathbf{x} \eta_{a} \mathbf{x} \eta_{o} \qquad (7.5)$$

where:

 η_0 = positional efficiency of the booster (-)

The driving force available per booster in the tunnel tube with *traffic* is calculated from:

$$\mathbf{I}_{\text{traffic}} = \rho \mathbf{x} \left(\mathbf{u}_{\mathbf{a}} - \mathbf{u}_{\text{eff}} \right) \mathbf{x} \mathbf{Q}_{\mathbf{a}} \mathbf{x} \eta_{\mathbf{a}} \mathbf{x} \eta_{\mathbf{o}} \qquad (7.6)$$

Modified impulse yield due to flow of surrounding air.

The flow of the surrounding air must be taken into account. The flow can have a positive modifying effect by causing a decease in the power consumption. But on the outflow side negative effects can occur. The cause of this still has to be researched but it is likely that the shape of the outflow opening is involved.

In the laboratory the impulse yield is usually measured in surrounding air which is stationary. From measurements taken from a booster in surrounding air which is flowing it has been shown that the impulse yield increases. During the test with stationary surrounding air an impulse yield of 82% was measured. For surrounding air at a speed of 5 m/s the output was 85% and at 10 m/s it was 87%. Research must be carried out to find out to what extent these results are applicable in practice for a setup in the tunnel tube. It is expected that the impulse losses measured in the tunnel situation over the whole row will be less than in the experimental setup. A difference of 5 to 10% is possible.

7.2.4. Total efficiency of the booster system

The total efficiency of the whole ventilation system depends on a large number of factors the most important of which are summarized as follows:

- position of the booster in the transverse profile
- dimensions of the "clearance space profile"
- diameter of the air current blown out of the booster
- difference in speed between the speed of the air blown out by the booster and that of the surrounding tunnel air
- distribution of the speed of the tunnel air over the cross section
- distance between the boosters
- use of deflection blades
- inflow and outflow coefficients
- hydraulic diameter
- length and cross section of the tunnel

When the total efficiency of a ventilation system is being considered, not only the system itself must be taken into account but also the structural implementation of the system. All the parts of the system are important.

To determine the quality of the ventilation system in an unambiguous way, all the variable effects must be excluded. External factors such as wind effects, traffic effects, etc. are not easy to quantify nor can they be measured in a simple way. Therefore the variable effects are excluded by determining the total efficiency.

Total efficiency is defined as the quotient of the energy transmitted to the tunnel air in the form of kinetic energy and the energy consumed from the power supplying mains:

$$\eta_{\text{tot}} = \frac{P_{\text{air}}}{P_{\text{mains}}} X100\%$$
(7.7)

where:

P _{air}	=	kinetic energy transmitted to	the	tunnel
		air		(kW)
Pmains		= energy consumed from t	he	power
		supplying mains (kW)

 P_{mains} must be measured near the main distributor. Possible step-up step-down facilities are therefore also measured and are therefore included in the losses.

The kinetic energy present in the tunnel air is given by:

$$P_{air} = \frac{Q_t X p_d}{1000}$$
(7.8)

where:

$$Q_t = A_t x u_t \qquad (m^3/s)$$

$$p_d = \frac{1}{2} x \rho x u_t^2 \qquad (Pa)$$

The speed u_t must be measured according to the method described in 12.4.7.

After substitution it follows that:

$$P_{lucht} = \frac{1.2xA_{t} x u_{t}^{3}}{2000}$$
(7.9)

The total efficiency of a booster system defined in the aforementioned way is low. This is not considered to be problematic because the number of hours in operation is only small. In normal circumstances the flow of ventilation is created by the traffic itself. The system only operates in the event of a traffic jam or in disasters.

7.3 LONGITUDINAL VENTILATION WITH A CLOSED INJECTOR

In this system the outside air is blown into the tunnel in the horizontal plane parallel to the axis of the tunnel tube and in the vertical plane tangentially at a small angle (5-20°) to the axis of the tunnel tube. The main difference from the booster system is that the air supplied is not supplied from the tunnel but from the outside air. In a variation of this the injector system compensates for the resistance of the longitudinal ventilation in long tunnel tubes such as those built abroad. In this variation the injector operates with tunnel air and is therefore like a booster with a large capacity. The tunnel air is circulated in a way which is similar to the booster principle. The injector opening is usually located at the beginning of submerged tunnels.

The calculation of the driving force supplied by this injector opening is made in the same way as that for the boosters. The driving force is related to the volume of the current of air, the exit speed in this inlet opening, the density of the air blown in and the angle at which the air is blown in.



FIGURE 7.1:

Injector near the entrance to the tunnel

Since the air blown in is sucked in from outside the tunnel, the temperature of this air can never be affected by a possible fire in the tunnel. The driving force supplied does not decrease as a result of the high air temperatures in the tunnel and the lower density of the air, which is a clear advantage compared to a system with boosters installed in the tunnel.

The value frequently used for the air speed of the injected air is

30-35 m/s blown in at an angle of $5-20^{\circ}$.

The possibility of air flowing back or short circuiting must be taken into account in these calculations. This depends on the pressures at the entrance, the position of the injection opening and the resistance in the tunnel tube and the exit, where the wind pressure is an important factor.

7.3.1 Calculation

Figure 7.2 is a diagram of a section of the tunnel tube with stationary traffic and an injector. Application of the impulse theory and the continuity equation on the control surface indicated in the figure, assuming that the flow is on average stationary and disregarding the mass force, results by approximation in:

$$p_{1} x A_{t} + \rho x A_{t} x u_{1}^{2} + \rho x A_{s} x u_{s}^{2} x \cos \alpha - P_{2} x A_{t} - \rho x A_{t} x U_{2}^{2} - R_{12} = 0$$
(7.10)
and

$$u_1 \ge A_1 + U_2 \ge A_2 = u_2 \ge A_1$$
 (7.11)

where:

ρ	=	density	of the	air	(kg/m³)
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- u_s = average speed of the injected air (m/s) u_1 = average air speed in the empty tunnel tube at
- the position of cross section 1 (m/s)
- u₂ = average air speed in the empty tunnel tube at the position of cross section 2 (m/s)
- A_t = surface area of the cross section of the tunnel tube (m^2)
- $A_s =$ surface area of the injector opening (m²) $\alpha =$ angle at which the direction of injected air meets the tunnel axis (°)
- p_1 = static pressure at the position of cross section 1 in the tunnel tube (Pa)
- p₂ = static pressure at the position of cross section 2 in the tunnel tube (Pa)
- R_{12} = resistance in the tunnel tube between the cross sections 1 and 2 (N)

By using the following notations:

$$f = \frac{A_s}{A_t}$$
 en $\in = \frac{u_s \times A_s}{u_2 \times A_t}$

it follows from (7.10) and 7.11) that:

$$\frac{p_2 - p_1}{\frac{1}{2} x \rho x u_2^2} = 2 \left\{ (1 - \Theta^2 + \frac{e^2}{f} x \cos \alpha - 1 - \frac{R_{12}}{\rho x u_2^2} \right\}$$
(7.12)



FIGURE 7.2: Road tunnel tube with traffic and the operating injector

The static reduction in pressure in the tunnel tube is also given schematically in Figure 7.2. Actually the increase in pressure near the injector builds up gradually in the mixing zone of the injector air. The length of the injector a and also therefore the loss of pressure over that distance are discounted in relation to the length of the tunnel.

The value of $p_2 - p_1$ is determined by losses in the flow of air at the entrance and exit openings of the tunnel and possible barometric pressure differences due to wind. If $p_2 - p_1$ is represented by p_u and substituted in the equation:

$$\zeta_{1} = \frac{R_{12}}{A_{1}} \times \frac{1}{\frac{1}{2} \times \rho \times u_{2}^{2}}$$

$$\zeta_{u} = \frac{\rho_{u}}{\frac{1}{2} \times \rho \times u_{2}^{2}}$$
 and

then it follows from (7.12) that:

$$\zeta = \zeta_u + \zeta_1 = 2 \left\{ \stackrel{2}{\leftarrow} x \frac{f + \cos \alpha}{f} - 2 \right\}$$
(7.13)

where ζ is the resistance coefficient of the tunnel tube and is related to the average speed of the air in the empty tunnel tube after the mixing zone of the injector. The impulse yield η_i of the injector can be defined as:

volume of air x increase in pressure in the tunnel tube

$$\eta i = \frac{1}{\sqrt{1 + 1}}$$
volume of air x increase in pressure in injector (7.14)

Since the injection speed u_1 is high in relation to the longitudinal speed u_2 in the tunnel tube and the pressure difference $p_2 - p_1$ is small in relation to Δp , the increase in pressure Δp in the injector follows from Bernoulli's equation:

$$\frac{1}{2} \times \rho \times u_2^2 + p_1 + \Delta p = \frac{1}{2} \times \rho \times u_8^2 + p_2$$
(7.15)

it applies that: $\Delta p = \eta_i$ is a good estimate.

 η can be written as:

$$\eta_{i} = \frac{u_{2} \times A_{i} \times \zeta \times \frac{1}{2} \times \rho \times u_{2}^{2}}{u_{s} \times A_{s} \times \frac{1}{2} \times \rho \times u_{s}^{2}} = \frac{\zeta \times f^{2}}{e^{2}}$$
(7.16)

The results of \in and η_i are plotted in Figure 7.3 for the different values of f against resistance R in the tunnel tube.

The graph shows that at a certain value of f, the amount of air carried along decreases (\in increases) as the resistance in the tunnel tube increases.

The injection output decreases accordingly. At a certain tunnel tube resistance $R \in$ increases as the values of f increase. It is even possible that \in is greater than 1, which means that injected air flows back. Then injection cannot be said to be working any more. It is also apparent from the graph that by enlarging the injection opening a considerable improvement in output occurs. The required motor output for the injection ventilators therefore decreases with larger injection openings and for that matter under similar conditions, as given in the definition of output and inversely proportional to the increase in output.

Any flowing back of the injected air does not cause a problem for an injector which is installed right next to the entrance of the traffic tube because air which flows back can disperse through the entrance and the longitudinal current in the tunnel tube is not affected. The volume of air flowing back and the size of the injection opening are limited by the occurrence of turbulence at the inlet opening. The circulation of air becomes unstable which can have a disruptive effect on the traffic.





FIGURE 7.3:

Impulse yield and tunnel resistance

Compared to a system in which a large number of small boosters are installed in the tunnel tube, the longitudinal ventilation system which uses injectors has the advantage that:

- the injectors do not disturb the tunnel profile
- the injectors can be maintained without disrupting the traffic
- "fresh" air is injected from outside the tunnel tube.

On the other hand the use of several boosters gives a greater reliability in operation, while the ventilation buildings can be converted into service buildings.

7.3.2 Total efficiency of the closed injector system

The total efficiency of the ventilation system depends on a large number of factors the most important of which are summarized as follows:

- position of the injector in the longitudinal profile
- dimensions of the "clearance space profile"
- diameter of the air stream flowing out of the injector
- difference in speed between the speed of the air blown out by the injector and that of the surrounding tunnel air
- losses in the duct system of the injector
- inflow and outflow coefficients
- roughness of the walls
- hydraulic diameter
- length and cross section of the tunnel tube

When the total efficiency of a ventilation system is discussed, not only the system itself must be considered but also the structural implementation of the system. All the parts of the system are important.

To determine the quality of the ventilation system in an unambiguous way, all the variable effects must be excluded. External factors such as wind effects, traffic effects, etc. are not easy to quantify nor can they be measured in a simple way. Therefore the variable effects are excluded by determining the total efficiency.

Total efficiency is defined as the quotient of the energy transmitted to the tunnel air in the form of kinetic energy and the energy consumed from the power supplying mains:

$$\eta_{\rm tot} = \frac{P_{\rm air}}{P_{\rm mains}} \times 100\% \tag{7.18}$$

where:

Pair	=	kinetic	energy	transmitte	d to	the 1	lunnel-
		air					(kW)
P	=	energy	consun	ned from	the	powe	r sup-

plying mains (kW)

 P_{mains} must be measured near the main distributor. Possible step-up step-down facilities are therefore also measured and are therefore included in the losses.

The kinetic energy present in the tunnel air is given in:

$$P_{air} = \frac{Q_t \times p_d}{1000}$$
(7.18)

where:

$$\begin{array}{lll} Q_t &= A_t \ x \ u_t & (m^3/s) \\ p_d &= \frac{1}{2} \ x \ \rho \ x \ u_t^2 & (Pa) \end{array}$$

After substitution it follows that:

$$P_{air} = \frac{1.2 \times A_t \times u_t^3}{2000}$$
(7.19)

Some values for the Coen tunnel are as follows:

$$A_t = 42.5 m^2$$

 $A_s = 4.9 m^2$
 $\eta = 25\%$

It follows from Figure 7.3 that the tunnel resistance is 80 Pa.

The injector is implemented by two ventilators. The energy consumed amounts to 41 kW for each ventilator with an output rate of 99 m_3 /s.

The calculated average air speed in the tunnel tube in calm weather conditions and no traffic is:

$$u_t = \frac{2 \times 99}{42.5} = 4.66 \text{ m/s}$$

The kinetic energy of the tunnel air is:

$$P_{\text{lucht}} = \frac{1.2 \text{ x } 42.5 \text{ x } 4.66^3}{2000} = 2.58 \text{ kW}$$

According to equation (7.17) this supplies a total efficiency of:

$$\eta_{\text{tot}} = \frac{2.58}{2 \times 41} \times 100 = 3.1\%$$

This efficiency level is low just like that of the booster system but is not considered problematic because of the reasons already given in the section on boosters.

7.4 LONGITUDINAL VENTILATION WITH AN OPEN INJECTOR

The way a system with an open injector functions has been described in Chapter 5 so reference is made to that chapter. Up to now such a system has not been applied in the Netherlands.

No recent research results are known for the open injector system. However, the output of such a system has been measured in the Guldborgsund tunnel in Denmark. The results of these measurements show that if the tunnel resistance is not too large, no flow back of air occurs. The sucking in effect by the tunnel opening was small in these measurements.

The calculations for the open injector are in principle the same as those for the closed injector.

The calculations are roughly as follows:

- 1. The volume of tunnel air which can be generated with a open injector matches the capacity of the ventilators installed in the injector.
- 2. Rule 1 only applies, if the total tunnel resistance is small. This total resistance can be compensated by the installation of boosters distributed along the length of the tunnel.

This leads to the third longitudinal ventilation system namely the combined system of an open injector and boosters distributed along the length of the tunnel.

7.5 LONGITUDINAL VENTILATION WITH AN OPEN INJECTOR IN COMBINATION WITH BOOSTERS

The way a system with an open injector in combination with boosters functions has been described in Chapter 5 so reference is made to that chapter. Up to now this system in this form has not been applied in the Netherlands. A combined system has been built in the Benelux tunnel but in this case a closed injector is combined with boosters distributed along the length of the tunnel.

The system with an open injector in combination with boosters distributed along the length of the tunnel can be considered as two separate systems which reinforce each other. The way in which the calculation must be made has not been researched yet. Research is necessary on the application of such a system. Until the results of this research have become available the following simplified method can be used:

- 1. Consider the open injector as a booster with a positional efficiency of 100%.
- 2. Consider the boosters distributed along the length of the tunnel to have a positional efficiency appropriate to the situation.
- 3. Calculate the driving force required and make a distribution of the power which must be supplied by the injector and by the boosters.

At the present time it is not possible to include better information in these recommendations and the aforementioned simplified method is sufficient to design such a system.

7.6 LOSS OF PRESSURE IN THE EMPTY TUNNEL TUBE

The calculation of pressure losses in the empty tunnel tube, or tunnel resistance, is analogous to the resistance calculation for air ducts and is described below. The following parameters are important: the hydraulic diameter, the wall friction coefficient, the resistance near the entrance and exit openings.

The presence of traffic in the tunnel causes a partial blocking of the cross section, which is not constant longitudinally. This may result in a local increase in the air speed giving rise to an increased loss of pressure.

The exact effect of this is not known yet and is calculated by means of a factor in the determination of the friction coefficient. Refer to 7.7 "Traffic effects" for more information.

7.6.1 Hydraulic diameter

To compensate for the deviation of the tunnel cross section from a circular cross section, a theoretical circular cross section is used, the hydraulic cross section, which has the same resistance as that of the tunnel cross section. The hydraulic diameter is defined as:

$$D_{h} = 4 x \frac{A_{t}}{O_{t}}$$

where:

 D_h = hydraulic diameter of the tunnel tube (m) A_t = surface area of the cross section of the tunnel

- tube (m²)
- O_t = circumference of the cross section of the tunnel (m)

7.6.2 Wall friction coefficient

The value of the wall friction coefficient cannot be given unequivocally. Different values are given for this coefficient in various publications. It is possible to determine the wall friction coefficient in a simple way by using the graphs in Appendix B.

Besides normal wall roughness (including an acoustic ceiling if fitted) the coefficient of wall friction must also take account of the various pieces of equipment in the tunnel tube, which can consist of light fittings, traffic lights, fire brigade cupboards, various recesses in which power supply, control and distribution boxes are fitted and suspension frames in particular.

The PIARC gives a friction coefficient of 0.025, including the additional resistances. Other references give lower values of 0.015. In the Holland tunnel a value of 0.014 was measured. In the Guldborgsund tunnel a value of 0.025 was derived at an air speed of 3 to 4 m/s. Since there is a difference in the values it is recommended that measurements of wall friction are systematically taken in tunnels which will be built in the future in the Netherlands.

Another method is based on a theoretical approach. The value of the wall friction λ_o depends on Reynolds number (Re), which in its turn depends on the air speed in the tunnel tube. The value λ_o can be determined from Coolebrook–White's equation:

$$\frac{1}{\lambda_{o}^{0.5}} = -2 \text{ x } \log \left(\frac{\in}{3.72 \text{ x } D_{h}} + \frac{2.51}{\text{Re x } \lambda_{0}^{0.5}} \right)$$

(7.21) The result is obtained by reiteration. In equation $(7.21) \in$ represents wall roughness in m.

Reynolds number is:

$$Re = u_t \times \frac{D_h}{v_i}$$
(7.22)

where:

(7.20)

Re	=	Reynolds number	(-)
D_h	=	hydraulic diameter of the tunnel tube	(m)
$\mathbf{v_1}$	=	kinematic viscosity of air	(m^2/s)
u ₁	=	average air speed in the empty tunnel	
		tube	(m/s)

The dependency of Reynolds number is as follows:

$$\lambda_{\rm w} = \lambda_{\rm o} \ x \ (\frac{{\rm Re}_{\rm o}}{{\rm Re}})^{0.2} \tag{7.23}$$

where:

 $\begin{array}{rcl} \lambda_{\rm w} &=& {\rm actual \ friction \ coefficient \ of \ the \ tunnel \ wall} & (-) \\ \lambda_{\rm o} &=& {\rm reference \ friction \ coefficient \ of \ the \ tunnel \ wall} & (-) \\ {\rm Re} &=& {\rm actual \ Reynolds \ number} & (-) \\ {\rm Re}_{\rm o} &=& {\rm reference \ Reynolds \ number} & (= 500,000) (-) \end{array}$

Calculations show that if the coefficient measured is 0.025, related to the reference Reynolds number of 500,000, is converted into the actual value, then a lower coefficient of 0.017 to 0.020 results, at normal air speeds of 2 to 6 m/s.

As long as no better values for this resistance coefficient are available, based on model testing or on actual measurements, the value 0.015 or 0.020 can be adhered to whether of not a Reynolds correction is made to the speed.

Calculation

The resistance as a result of the tunnel wall friction is calculated from:

$$\mathbf{R}_{\text{leeg}} = \lambda_{\text{w}} \times \frac{\mathbf{L}}{\mathbf{D}_{\text{h}}} \times \frac{1}{2} \times \rho \times \mathbf{u}_{\text{t}}^2 \times \mathbf{A}_{\text{t}} \quad (7.24)$$

where:

 R_{empty} = resistance of the empty tunnel tube (N) λ_w = actual friction coefficient of the tunnel wal (-)

$$L = length of the tunnel tube (m)$$

D _h	=	hydraulic diameter of the tunnel tube(m)
ρ	=	density of air (kg/m ³)
u _t	=	average air speed in the empty tunnnel
		tube (m/s)
At	=	surface area of the cross section of the
		tunnel tube (m ²)

7.6.3 Inflow and outflow losses

The resistance values at the entrance and exit openings are related to the air speed by using the inflow and outflow coefficients ζ_{in} and ζ_{out} .

The PIARC gives 1.4 as the sum of ζ_{in} and ζ_{out} . By paying more attention to the shape of the inflow opening, in which the effect of the sun-excluding grid structure must not be forgotten, the inflow coefficient can be reduced. To reduce the exit coefficient fundamental measures are required with respect to the technical aspects of shape. The shape of the exit opening will not result in an easy reduction of this coefficient. The exit or outflow coefficient will not be reduced by a small rounding off of the exit because the air flow cannot follow the angle of widening (no contour effect), as a result of which all the velocity pressure and the subsequent turbulence account for the losses on the outflow side. This loss can only be restricted by reducing the speed of the tunnel air. A very gradual increase in the cross section of the tunnel (works as a diffuser) is necessary to achieve this reduction in speed. Since in a reversible system the exit opening becomes the entrance opening with respect to the flow of air, this must also be taken into account.

In existing tunnels with sun-reflecting grids at the entrance it has been shown that the inflow coefficient lies between 2 and 3. The high losses associated with this, which are caused by the bad aerodynamic shape of the slats used in the sunreflecting grid, are considerably higher than has been assumed up to now. A substantially lower coefficient, for example 1.5, can be used for tunnels without grid structures. It is suggested that a value of 1.2 for the sum of the inflow and outflow coefficients should be aimed at for tunnels still to be built by finding appropriate aerodynamic measures. If this is not possible then a higher value must be considered, for example 1.5 to 2.

For tunnels which are still to be built it is recommended that measurements are taken during the checking of the dimensions of the ventilation system from which the correct values for the inflow and outflow coefficients can be derived to ensure that better numerical values are available in the future.

Calculation

If the cross sections of the entrances and exits are the same, both coefficients can be included in one equation because the air speeds are equal. If this is not the case, as with an injector, then a separate calculation is made for the incoming and outgoing side.

The equation is as follows for an empty tunnel tube:

$$R_{in/out} = (\zeta_{in} + \zeta_{out}) \times \frac{1}{2} \times \rho \times u_t^2 \times A_t$$
(7.25)

where:

R _{in/out}	=	sum of the resistances across the en	Irance
		and exit openings	(N)
ζ _{in}	=	inflow coefficient at the entrance	ope-
		ning	(-)
ζout	=	outflow coefficient at the exit	
		opening	(-)
u	=	average air speed in the empty	
		tunnel	(m/s)
A,	Ħ	surface area of the cross section (of the
		tunnel tube	(m²)

The values of the inflow and outflow coefficients ζ_{in} and ζ_{out} are determined by the shape of the traffic tube at the entrance and exit and their position in the surroundings.

In a tunnel tube filled with traffic the effective air speed involved in the remaining smaller cross section must be taken into account. Taking the traffic into consideration the combined resistance at the entrance and exit openings is:

$$R_{in/out(traffic)} = (\zeta_{in} + \zeta_{out}) \times \frac{1}{2} \times \rho \times u_{eff}^{2}$$
(7.26)

$$\times (A_{t} - A_{v})$$
 where:

- u_{eff} = effective air speed in the tunnel tube filled with traffic (m/s)
- = total aerodynamic surface area of traffic in the cross section of the tunnel tube (m^2)

7.7. EFFECT OF TRAFFIC

Resistance or suction effect 7.7.1

The traffic can either be a resistance in the air stream or it can add to the available driving force of the boosters, the so-called suction effect. This is determined by the speed of the traffic in relation to the air speed in the tunnel tube. If the speed of the traffic is higher, then the traffic supplies a positive contribution to the driving force available.

7.7.2 Number and type of vehicles

Chapter 4 has dealt with the traffic lane capacity in the Dutch situation. Therefore this chapter is referred to for the numbers of vehicles according to type and traffic lane.

If no information is available about the traffic because for example a calculation has to be made for a tunnel in another country, then the following outline method according to the PIARC recommendations can be used. The distance between two vehicles is estimated here to be equal to the speed of the traffic, expressed in kilometres per hour, divided by two. By adding on an average vehicle length of 5 m the centre-to-centre distance between two vehicles is found. This can then be used to work out the number of vehicles in each traffic lane.

In the event of a total traffic jam in the tunnel, thus with the speed of the traffic being 0 km/h, the above-mentioned method cannot be used. The PLARC reports that the traffic density in this situation is 140 vehicles per kilometre per traffic lane. In comparison Chapter 4 gives a density of 145.15 vehicles/km traffic lane with 100% cars.

7.7.3 Resistance of traffic

The actual resistance of a vehicle in a tunnel has hardly been researched. Up until now the product of the so-called drag coefficient has been used (resistance coefficient) and the frontal cross sectional area of the vehicle represented by the ($C_w \times A^{-1}$) value.

The frontal cross section of a vehicle (A^{\perp}) is an invariable and can be easily measured and checked. The resistance coefficient supplied by the various vehicle manufacturers must be used cautiously. This coefficient is often determined under laboratory conditions without accessories, with the flow of air coming from the front and applicable to the individual vehicle. The circumstances in a tunnel can deviate a great deal from this. In the worst situation (stationary traffic) the air flow comes from behind, while there is always a queue of traffic lined up. The chance also exists of fully laden vehicles with roofracks and fully laden goods vehicles which also increases the resistance. The PIARC gives a value of 1 m^2 for this (C_wxA-) value for cars and 3 to 5 m² for goods vehicles. Other recommendations give values of 1 and 7 m² for cars and goods vehicles, respectively.

By using these average values and assuming that the effect of increasing resistance caused by air flowing from behind is removed by the effect of decreasing resistance caused by the formation of a line of traffic, the value used will not deviate very much from the "actual" value.

The effect of the formation of a line of traffic or "shadow effect" depends on the distance between the moving or stationary vehicles. At a distance of 3.6 car lengths between the vehicles the effect is already noticeable, while at a distance of 1.3 car lengths a considerable reduction in the coefficient of resistance occurs. The reduction can be as much as 90%.

Tests on models, carried out by Novenco on the instructions of the Civil Engineering Division of the Directorate–General for Public Works and Water Management, show this shadow effect. This research shows that the resistance of a stationary line of vehicles amounts to a maximum of 50% of the sum of the individual resistances. For this reason it is advisable that in the case of stationary traffic or at speeds lower than 10 km/h to reduce the C_w value given for the individual vehicles by half. With a constant frontal cross section the vehicle resistance is also reduced by half.

In the calculation method given below another correction for the shadow effect is applied. Application of this method gives higher resistances than if the C_w value is halved. The reader is given the choice of the method used.

Calculation of vehicle resistance

The extent of the vehicle resistance depends on the number and type of vehicles, their distance from each other – the vehicle line–up –, the position of the vehicles in the cross section of the tunnel and the speed of the traffic with respect to the speed of the tunnel air.

The vehicle resistance can be calculated from:

$$R_{\text{traffic}} = C_{\text{w traffic}} x \frac{1}{2} x \rho(u_t - u_v) x |u_t - u_v| x n_r x L$$
(7.27)
where:

R _{traffic}	=	resistance of the traffic in the	tunnel
		tube	(N)
C _w	=	air resistance coefficient of the	
		traffic	(-)
u _t	=	average air speed in empty tunnel	
		tube	(m/s)
u,	=	speed of the traffic	(m/s)
n,	=	number of traffic lanes	(-)
L	=	length of tunnel tube	(m)

The distribution of the traffic over goods vehicles and cars, the number and the traffic line-up are included in $C_{w \text{ traffic}}$.

The resistance of an individual car or goods vehicle is determined by its cross sectional area and its coefficient of resistance. In general the following values are adhered to:

car	:	aerodynamic surface area $(A \perp_{pa}) = 2.0$	(m²)
		coefficient of resistance $(C_{w p}) = 0.55$	(-)
goods	:	aerodynamic surface area $(A_{vi}) = 6.5$	(m ²)
		coefficient of resistance $(C_{w y}) = 1.0$	(-)

If the cars stand close behind each other, the individual resistance decreases. This so-called shadow effect depends on the distance between the vehicles. This effect can be calculated as follows:

If the percentage of goods vehicles > 0% then:

$$C'_{w va} = 0.5 \text{ x } C_{w pa}$$
(7.28)
$$C'_{w va} = C_{w va} - 6 \text{ x } C_{w va}^{2} \text{ x } A^{\perp}_{pa} / \{\text{ctc}\}^{2}$$
(7.29)

where:

C' _w pa	=	reduced air resistance coefficient of car
		(pa) (-)
C' _{w va}	=	reduced air resistance coefficient of
		goods vehicles (va) (-)
ctc	=	centre-to-centre distance between goods
		vehicles (m)
	=	$\{(\% \text{ va}) \times (\text{ctc distance va}) +$

$$= \{(\% \text{ va}) \times (\text{ctc distance va}) + (\% \text{ pa}) \times (\text{ctc distance pa})/(\% \text{ va}) \}$$

If the percentage of goods vehicles is 0% then:

$$C'_{w pa} = C_{wp} - 6 \times C_{wp} - 6 \times C_{w pa}^{2} \times A \perp_{pa} /{\text{ctc}}^{2}$$
 (7.30)

where:

ctc = centre-to-centre distance between cars (m)

An average value can be calculated for the resistance coefficient of the vehicles by using the traffic composition, which gives the ratios of the various vehicle categories. The traffic lane capacity cited in Chapter 4 of these recommendations is used as the basis for this.

If the total number of goods vehicles and cars per metre of traffic lane is represented by n_{pa} and n_{va} , respectively, it applies to the total resistance coefficient of the traffic that:

$$C_{w \text{ traffic}} = n_{pa} \times C'_{wpa} \times A \perp_{pa} + n_{va} \times C'_{wva} \times A \perp_{va})$$
(7.31)

7.8 EFFECT OF WIND

The effect of wind is often a determinative factor for the capacity of the ventilation system because of the geographical nature of the Netherlands and other flat countries. The effect of wind is certainly decisive in tunnels which have exits at ground level or even above ground level. A lot of attention has been paid to this point in the past and one of the solutions which has been considered is making the ventilation system reversible.

The underlying idea is simple for the wind is a source of energy which can be used to back up the system. By using a suitable control system (see Chapter 13) the capacity of the mechanical ven-tilation system is significantly reduced. The possibility of fire must, however, be taken into account here. This has been discussed extensively in paragraph 5.6.

The ventilation system must have sufficient capacity to give the flow of air in the tunnel a certain desired speed which can be effective against a certain wind pressure. These basic assumptions depend on probability to a large extent and therefore a probabilistic calculation method has been applied so that designs can be made which fit in better with the practical situation. For details about this refer to Chapters 8 to 11.

This section deals with the factors which effect the result of the calculation. Attention is paid consecutively to:

- orientation and position

- wind speed

effect of shape (the shadow effect)speed and direction of the ventilation.

7.8.1 Orientation and position

The orientation of the tunnel opening with respect to the prevailing wind direction or the wind direction with the highest wind speeds is important. The entrance as well as the exit play a role here. Both these openings are usually in line with each other so that one encounters a counter pressure and the other a suction effect resulting from the wind pressure. If the orientations of the openings differ from each other, the correct position for each wind direction must be studied and the joint effect on the ventilation system assessed.

The position of the opening with respect to the direction of the wind determines to a large extent whether or not the wind pressure is overcome. If the opening lies below ground level or totally above ground level, the openings can be framed by a vertical wall or high walls can be built. These are all things which can reduce the eventual effect of the wind pressure or even increase it: consider a funnel shape which can produce a driving force larger than the wind pressure.

Since the wind has such a large effect on the end result, it is advisable that model tests are carried out to determine the correct values of the wind pressure factors. If a tunnel design is concerned in which the exits do not run parallel to each other, it is certainly difficult to give a reliable estimate of the wind pressure factors and preference should decidedly be given to model tests.

Appendix D gives more information about the effect of wind and orientation as outlined in a pressure coefficient by the Hydraulic Engineering Department of the Civil Engineering Division.

7.8.2 Wind speed

In assessing different data on wind speeds the height at which these speeds have been measured must be noted. The meterological stations are usually located at a height of 15 to 25 m above ground level and the values measured are frequently converted to 10 m above unrestricted ground level. To avoid confusion it is advisable from now on to only use wind speeds measured at a height of 10 m above the open field. The wind tables published by the KNMI (Dutch Meterological Institute) normally provide these values. The reason for this is that tunnels are usually built below this height and there is no need for speeds measured at greater heights as is the case for tall buildings.

The wind speed is always lower at the height of the entrance and exit of the tunnel because the surface of the ground curbs the wind speed. This reduced wind speed determines the driving force to which the wind pressure is related in the tunnel openings.

In carrying out model tests the roughness of the surface of the earth is corrected for by making the floor of the wind tunnel rough in the flow zone in accordance with a certain standard. The values for wind pressure measured in this way on the tunnel opening in the model do not have to be corrected for height.

However, a model test is not often carried out and the wind speeds measured at the meteorological stations must be corrected for the surface roughness of the ground.

7.8.3. Shadow factor

The shadow factor (or shape factor) represents the effect of the shape of the tunnel entrance and the position of the tunnel opening with respect to the immediate surroundings. This factor should be clearly defined. Table 7.1 only gives information about the effect of the tunnel entrance and not of possible buildings in the immediate vicinity.

TABLE 7.1:

V	alu	es i	tor	the	shadow	factor	S_w
---	-----	------	-----	-----	--------	--------	-------

situation	position of the entrance/exit		
	aboveground	underground	
wall above entrance/exit, with a central wall	0.75	0.65	
with only a dividing wall	0.55	0.55	
wall above entrance/exit, extended walls	0.45	0.40	
tunnel with extended	0.30	0.20	
in a smooth (mountain)	1.0 to 1.2		
cut below ground level		0.8	

It must be emphasized that these values are only rough estimates. As indicated above a model test is the best way of getting more accurate results.

Besides the shadow factor possible buildings in the immediate vicinity which are not part of the tunnel should be taken into account. An example of this is a factory or flats in the vicinity of the tunnel entrance. Buildings of any size within a radius of 100 m should be considered. Buildings taller than 50 m have an even more noticeable effect and must be taken into account, if they are within a radius of 200m.

7.8.4 Speed and direction of ventilation

As has been noted above the direction of the ventilation affects the wind pressure on the tunnel openings. Wind pressure is increased, if the direction of the ventilation and the wind are the same. If the ventilation and the wind are in opposite directions, wind pressure is reduced.

Apart from wind pressure being affected by the direction of the ventilation in the tunnel, as indicated above, the ratio of the wind speed to the air speed in the tunnel tube is important. If this ratio increases, the effect of wind pressure also increases.

Since a tunnel tube has two openings where both mechanisms operate the total result depends on the extent of the increase or decrease in the effect of the wind. Since the increase, which is due to the direction of ventilation flow being the same as that of the wind, is larger than the decrease due to the flow of ventilation in the opposite direction, the final result is that the effect of the wind is greater than would be expected based on the existing literature.

It is suggested that the simplified calculation given in Appendix D is used. This calculation can be adjusted as soon as more research has been carried out on this phenomenon.

7.8.5 Calculation of wind resistance

The impulse losses as a result of wind pressure on the tunnel openings can be expressed in:

$$R_{wind} = C_{w} x \frac{1}{2} x \rho x u_{w}^{2} x A_{p}$$
(7.32)

where:

\mathbf{R}_{wind}	=	resistance as a result of the wind pressure
		difference across the entrance and exit (N)
C "	=	driving force coefficient for the wind pres-
		sure (-)
u "	=	wind speed at the tunnel opening (m/s)
A _n	=	surface area of the cross section of the
r		tunnel tube at the opening (-)

One of the few measurements which have been taken for wind pressure on tunnel openings concern the measurements made by the NLR (National Air and Space Laboratory) on the Schiphol tunnel. This tunnel can broadly speaking be considered as being representative of tunnels in the Netherlands with the proviso that there are no buildings in the immediate surroundings of the tunnel.

An analysis of these measurements shows that the thrust coefficient depends on:

- the wind direction in relation to the tunnel axis
- the ratio u_{u}/u_{t}
- the direction of u,
- the tunnel geometry

In Appendix D the NLR results are represented as a pressure coefficient curve. In this appendix the pressure coefficient is expressed as:

$$C_w = \alpha_{w1} \times u_t/u_w + \alpha_{w2} \tag{7.33}$$

Where α_{w1} and α_{w2} are coefficients which are related to the wind direction, the value of which is determined by the tunnel geometry and the direction and level of u_t . Some explanation about α_{w1} and α_{w2} is provided in Appendix D. The coefficient is different for each wind direction which means that a large number of calculations must be made to be able to determine the normative coefficient. A procedure has been included in the probabilistic calculations which produces results quickly.

The *local* wind speed at a height of 10 m must be substituted in equation (7.32). However, it is often the case that only the converted data from a meteorological station are available. These data relate to the wind speed at 10 m above unrestricted ground level.

By multiplying the wind speed measured at the meteorological station by a surroundings factor which depends on wind direction, the so-called ground roughness factor, the local wind speed can be determined at a height of 10 m. In Table 7.2 the following values are given for the ground roughness factor based on a ground roughness classification.

TABLE 7.2: Values for ground roughness factor $\alpha_{environment}$

class.	description	type	rough- ness- factor
1	Open sea or lake, inres- tricted strech of at least 5 km	sea	1,12
2	Mud flats or snow surface, no plant growth or obstacles	smooth	1,06
3	Meadowland or fallow farmland with almost no obstacles, runways of airports	open	1,00
4	Farmlands with low crops, a few spread out obsta- cles at a fairly large distance from each other (>20 x obstacle height)	approx. open	0,94
5	Arable land with distri- buted obstacles, hedges, tall crops (e.g. corn)	rough	0,88
6	Woods, low buildings, with a frequently occurring, fairly dense covering of obstacles (space between = obstacle height)	very rough	0,82
7	Town with tall buildings (wind estimate not applicable)	closed	

In addition to this ground roughness factor the local direction-related effects, such as the presence of for example buildings near the entrance and exit openings, should also be taken into account by means of the shadow factor.

7.9 DETERMINATION OF THE AIR SPEED IN THE TUNNEL

By substituting equations (7.6), (7.24), (7.25), (7.26), (7.27) and (7.32) in the impulse equation:

$$I_{tot} = R_{empty} + R_{traffic} + R_{in/out} + R_{wind}$$
(7.34)

gives after some simplification the following quadratic equation in u_t :

$$a x u_t^2 + b x u_t + c = 0$$
 (7.35)

where:

$$a = (L \ x \ \lambda_w) + (L \ x \ n_r \ x \ C_w \ traffid} A_t) + (\zeta_{in} + \zeta_{out})$$

$$b = (-L \ x \ n_r \ x \ C_w \ traffid} A_t \ x \ u_v) + (\alpha_{w1} \ x \ u_{wind}) + (2 \ x \ \eta_{tot} \ x \ na \ x \ Q_a \ x \ A_{cff} A_t)$$

$$c = (L x n_r x C_{w traffic}/A_t x u_v^2) + (\alpha_{w2} x u_{wind}^2) - (2 x \eta_{tot} x n_a x Q_a x A_{eff}/A_t x u_a)$$

where:

α_{w1}	=	wind pressure coefficient	(-)
α_{w2}	=	wind pressure coefficient	(-)
A _{eff}	=	surface area of the effective cross	section
		of the tunnnel tube	(m ²)
C _{w traffic}	=	air resistance coefficient of the tra	ffic(-)
A _t	=	surface area of the cross section	of the
•		tunnel tube	(m ²)
ζ _{in}	=	inflow coefficient at the entrance	(–)
Sout	=	out flow coefficient at the exit	(-)
n,	=	number of traffic lanes in use	in the
		tunnel tube	(-)
L	=	length of the tunnel tube	(m)
η_{tat}	=	total efficiency of the ventilation	. ,
		system	(-)
n,	=	number of boosters in the tunnel	
•		tube	(-)
Q,	=	air flow rate of the booster	(m^3/s)
u,	=	average air speed in the outlet open	ning of
-		the booster	(m/s)
u,	=	average air speed in the empty	. ,
		tunnel	(m/s)
u,	=	speed of traffic	(m/s)
u.	=	local wind speed	(m/s)
WING			、)

 u_t can be determined from the quadratic equation (7.35), taking into account the fact that there are two possibilities:

a. The resulting air speed in the tunnel is positive (this means that it goes in the same direction as the traffic from entrance to exit).

Two possibilities can be distinguished here:

- the air speeds in the tunnel are greater than the speed of the traffic. In this case the traffic forms a positive resistance or in other words the traffic is not a driving force but a counter force
- the speed of the air is lower than the speed of the traffic with the result that the traffic creates a driving force due to the thrusting action.
- b. The resulting air speed in the tunnel is negative (this means that it is in the opposite direction to the traffic). This can be the case for example with a strong head wind, in which the wind pressures are so high that the resulting air flow is in the opposite direction to that of the ventilation.

The above-mentioned situations are represented in Table 7.3.

TABLE 7.3:

Possible speed situations

	3	2		1
< >	ut uv	-> ut > uv	> >	ut uv
ut = ut <	negative <- O	0 -> ut = positive 0 ≤ ut ≤ uv	ut≥	uv

The air speed in the tunnel tube is determined based on the following procedure:

Situation 1,

where $0 \le u_v \le u_t$

In this case all resistances are positive, which means they work as a counter force against the ventilation. It must be checked if one or both solutions are satisfactory. If neither solutions satisfy the assumption, then obviously the wrong assumption has been made and situation 2 or 3 must apply.

Situation 2, where $0 \le u_t \le u_y$

The air speed in the tunnel is still positive but lower than the traffic speed. The traffic which in situation 1 provided a resistance to the air flow in the tunnel is now a driving force (operating a thrust). Therefore it roughly applies that:

 $C_{w \text{ traffic}} = -C_{w \text{ traffic}}$

The remaining resistances do not change.

It is then checked if one or both solutions satisfy the assumption of situation 2. It also applies here that only one solution is possible.

If neither solution satisfies the assumption, then situation 3 applies.

Situation 3, where $u_i < 0$

In this case the tunnel resistance becomes negative and the inflow and outflow coefficients at the entrance and exit openings are reversed.

The vehicle resistance has already changed from having a positive sign in the calculation for situation 2.

It is then checked if one or both solutions satisfy the assumption of situation 3.

7.10 EFFECT OF FIRE ON THE VENTILATION SYSTEM

A fire in a tunnel has an effect on the ventilation calculation. Several factors must be taken into account of which the most important are:

- the size of the fire

- the density of the air/fumes due to the rise in temperature

- the fall in pressure over the source of the fire
- the temperature resistance of the ventilation system
- the behaviour of the smoke

- the poisonousness of the fumes.

These factors are discussed in sequence. It must be emphasized that the information provides no guidelines or starting points. The intention is only to offer help to the reader by providing background information which clarifies the problem of a fire in a tunnel.

7.10.1 Magnitude of the fire

The magnitude of the fire determines in fact the temperature of the air flow from the fire is given by:

$$\Delta t = \frac{Q}{A_t x u_t x \rho x c}$$
(7.36)

where:

- = rise in temperature of the air flow Λt (K)
- 0 = fire output (kW)
- = surface area of the cross section of the A, tunnel tube (m^2)
- = average air speed in the tunnel tube (m/s)u_t с

```
= specific heat of the air
                                     (kJ/kg K)
```

It is assumed here that all the output of the fire is transmitted to the air. Some of the energy will, however, be transmitted to the walls, ceiling and the road surface by radiation and convection of the flames and/or fumes.

The cooling effect is discounted in equation (7.35) as

a result of which the calculated temperature of the out flowing air is higher than it is in reality. By not taking the cooling effect into account it is assumed that the temperature downstream from the fire remains constant over the rest of the length of the tunnel. This means that if the calculated temperature is higher than the temperature to which the boosters are resistant, all boosters downstream from the fire will break down and therefore should not be included in the ventilation calculation.

The contribution to the cooling effect made by the walls, ceiling and road surface has been allowed for in the computer program calculations of the Centre for Fire Safety TNO-Engineering but is too complicated to be easily included in the calculation. The program makes it possible to calculate the temperatures arising, the quantities of fumes, the radiation intensity, the flow pattern and the fall in pressure over the source of the fire. It is shown from calculations that at low ventilation speeds in the tunnel tube considerable cooling occurs. The calculations at a ventilation speed of 2 m/s give the result that even in the event of a "large" fire the temperature is reduced to 300°C 300 m from the fire. At a ventilation speed of 5 m/s this distance increases to 500 m before the temperature of the fumes falls below 300°C.

Of course the temperature in the tunnel tube is only important with respect to the boosters installed there. With an injection system this temperature is not important if the injector operates with outside air.

The following values can be adhered to for the output of the fire:

- 3 MW for cars
- 10 MW for vans
- 20 MW for goods vehicles or coaches/buses
- 50 MW for petrol tankers
- 100 MW for large petrol tankers

If a tanker with 50 m^3 of petrol is completely burnt, 300 MW of energy is released. The amount of this energy required to keep the fire burning and the amount radiated to the concrete walls can only be calculated by the computer program developed by TNO.

If it is assumed that a proportion of the (liquid) fuel flows away down the drainage system, the amount available for combustion is smaller and the duration of the fire is shorter but the intensity remains unaltered, if the surface area of the source of the fire is not reduced.

The "fire" scenario used by the Civil Engineering Division assumes three possibilities, namely:

- 2.1 MK for a car fire
- 100 MK for a goods vehicle with trailer loaded with wood
- 300 MW for a tanker filled with 50 m^3 of petrol

The choice of the size of the fire determines the capacity of the ventilation system to a large extent. One of the factors which contributes to the choice is the nature of the transport. Whether a tunnel has or has not been opened to the transport of dangerous substances can be a decisive factor in the choice of the size of fire. See Chapter 2 "Background information for design scenarios" for more information.

7.10.2 **Density of the air/fumes**

For a ventilation system with boosters the decrease in density due to the higher air temperatures away from the source of the fire has the consequence that the boosters work less efficiently. The driving force of a booster is after all directly proportional to the density of the air.

"Standard" air at 20°C has a density of 1.2 kg/m³, while at a temperature of 250°C it is 0.67 kg/m³.

This means that roughly 60% of the driving force of the boosters away from the fire will be lost and that the number of boosters to be installed must be increased accordingly.

Apart from this phenomenon the higher speeds in the tunnel downstream from the fire must also be taken into account. The exit loss increases, which works to increase the required capacity of the ventilation system. This additional exit loss must be taken into account in a booster as well as in an injector system.

In the event of a fire of some size the rise in temperature results in a volume increase and therefore an increase in speed, as a result of which the air resistance increases. The density decreases but on balance resistance increases. This is illustrated below for a tunnel in which it applies that:

 $\begin{array}{rl} L &= 400 \mbox{ m} \\ A_t &= 65 \mbox{ m}^2 \\ D_h &= 7.45 \mbox{ m} \\ \lambda &= 0.02 \end{array}$

To circulate tunnel air at 20° C at a speed of 3 m/s over a distance of 400 m, the total pressure dif-

ference required is 11.7 Pa. At 250°C a pressure difference of 19.9 Pa is required.

7.10.3 Fall in pressure over the source of the fire The source of the fire creates a driving force for the air in the tunnel. In the event of a fire in the middle of the tunnel, if there are no other forces present, an air flow will be created towards both tunnel openings. The hot combustion gases flow at the top of the tunnel cross section towards the tunnel opening, while the air of combustion flows in at the bottom. To drive the fumes to one end of the tunnel an external force must be exerted on the source of the fire to overcome the loss of pressure over the source of the fire. To be able to drive the energy of the source of the fire in one direction a pressure difference is required which can reach more than 140 Pa in a "large" fire. The ventilation system must be capable of overcoming this pressure difference.

Calculations made at the Centre for Fire Safety TNO-Engineering have shown that to prevent the air flowing back a minimum fall in pressure over the source of the fire must be overcome. The fall in pressure over the source of the fire depends on the development of the fire, the size of the fire and the density of the combustion gases. To give an indication of the magnitude of the fall in pressure several values are given in Table 7.4 for a tanker fire of 300 MW related to the ventilation speed.

TABLE 7.4:

Fall in pressure over the source of the fire in the event of a tanker.

ventilation speed (m/s)	fall in pressure over the source of the fire (Pa)
1	40
2	70
3	100
5	140

The above-mentioned fall in pressure over the source of the fire has not been included in the calculation up to now. This phenomenon has only recently been recognized. As soon as the data from the TNO have been verified based on the fire tests which were made in America in 1991, it is advisable to take this fall in pressure into account in the future. For the time being a correction for this phenomenon should be included in the current calculation. Since the numerical values still do not have a definitive character it is proposed that a certain minimum air speed requirement is assumed in the zone of the fire. This minimum air speed requirement follows from

the volume of air necessary for the complete combustion of the fuel and the cross section. With the "large" fire scenario a minimum of 88 m³/s of air is required for the combustion of petrol on an evaporating surface area of 150 m³. The minimum air speed follows from this depending on the surface area of the cross section of the tunnel tube.

7.10.4 **Resistance to high temperatures**

There is a main difference between a booster system with boosters installed in the tunnel tube and an injector system operating with outside air. The boosters are not resistant to temperatures higher than 250 to 300°C due to technical limitations. The highest temperature limit of 300°C is only applicable for a very short time. At a temperature of 250°C the booster can be reckoned to function for 1 hour. After being exposed to these high temperatures replacement or overhaul must take place.

It is a great advantage that the above-mentioned limitations do not of course apply to an injector system with outside air. Therefore the most recent insights in this field are going in the direction of a combination of both systems to make use of the advantages of both systems. For more information see Chapter 5 under 5.4 "Longitudinal ventilation".

7.10.5 Behaviour of smoke

A basic assumption for a fire-resistant longitudinal ventilation system is that the fumes and combustion gases produced during the fire must not flow back in the opposite direction to that of the traffic. As a result of this people from stranded vehicles can have a smoke-free escape route and the fire brigade can control the source of the fire in a smoke-free atmosphere. The chance of people surviving in the tunnel is determined to a large extent by whether or not hot combustion gases flow back into the tunnel. Undesirable flowing back must therefore in principle not occur.

It is assumed that the traffic downstream from the fire (accident or crash) can leave by the tunnel exit. See also Chapter 5 under 5.6 "Fire and the ven-tilation system".

To be able to give the system the dimensions which will prevent "flow back", several approaches can be followed:

- By making a calculation with the calculation

program available at the Centre for Fire safety TNO-Engineering and/or using the indicated values given for this under 7.10.3 "Fall in pressure over the source of the fire".

- By choosing the PIARC approach for which the speed of the circulated cold air is used. The criterion (the limit value) is based on the type of fire or the output of the fire. The minimum air speeds to prevent flow back in car fires, a light goods vehicle or a tanker are 3, 5, and 7 m/s, respectively.
- Another method, based on the air temperature which arises, uses Froudes number. After theoretical and experimental research in America it has been shown that this number may not go above a certain value, above which flow back will certainly occur. This value lies between 4.5 and 6. For safety reasons the value of 4.5 can be taken. The range 4.5 to 6 can be seen as an indication of the margin. Froudes number is defined as:

Fr =
$$(\rho_1 - \rho_2) \times g \times \frac{h}{\rho_1 \times u_1^2}$$
 (7.37)

where:

Fr	Ŧ	Froudes number	(-)
ρ	=	density of the air upstream of the	
		fire	(kg/m^3)
ρ_2	=	density of air downstream from the	
		fire	(kg/m^3)
g	=	the acceleration of gravity	(m/s^2)
h	=	average height of the tunnel tube	(m)
u,	=	average air speed in the tunnel tube	e before
-		the fire	(m/s)

By using the approximation $\rho_1/\rho_2 = T_1/T_2$, Froudes number can also be expressed as:

Fr =
$$(T_2 - T_1) \times g \times \frac{h}{T_2 \times u_1^2}$$
 (7.38)

where:

- T_1 = absolute temperature of the air upstream of the fire (K)
- T_2 = absolute temperature of the air downstream from the fire (K)

7.10.6 Poisonousness of the fumes

Apart from the high temperature of the fumes, the poisonousness of the fumes is also a danger to the health of the people in the tunnel. As already reported in 7.10.5 preventing the flowing back of hot/poisonous fumes is in principle being aimed at.

It is also possible as a result of an accident without fire that poisonous substances are released. It may also be necessary in such a situation to use the ventilation system to create a ventilation flow over the place of the accident. The ventilation speed can in this case be at a minimum because there are no requirements for the volume of air with respect to complete combustion. The only requirement is to prevent flowing back. This not an normative situation for the capacity of the ventilation system.

It is also possible that the emergency service personnel decide to dilute the substance which has leaked out as much as possible to reduce the danger. In that case the maximum ventilation output will be put into operation. This situation is also not the starting point for the ventilation calculation.

7.10.7 Ventilation calculation in the event of fire To calculate the capacity of the ventilation system with boosters the following must be taken into account, among other things:

For the purpose of the calculation in the event of fire the tunnel can be divided into two parts. One part of the tunnel before the fire, the other part after the fire. The ventilation calculation for the part of the tunnel lying before the site of the fire can take place "normally" according to the method discussed above. The effect of temperature must be included for the part of the tunnel downstream from the fire, assuming that the longitudinal ventilation system blows the fumes arising from the fire in the same direction as the traffic.

The exit losses due to the increased speed near the exit must be included. The increased resistance due to the higher speeds in the zone downstream from the fire must also be allowed for in the calculation.

The decrease in the density of the air at high temperatures results in the lowering of the driving force of the boosters. At 250°C the driving force is reduced to approx. 60% of the original value at 20°C. This must be taken into account in the "large" and "medium-sized" fire scenarios by reducing the driving force of the boosters installed downstream of the fire by 60%, in as far as they remain working. In the "small" fire scenario no loss of driving force is taken into account.

Depending on the intensity of the fire one or more boosters will break down. Calculations indicate that at higher ventilation speeds the temperatures reached are higher than at lower speeds. The explanation for this somewhat strange phenomenon is that the cooling effect lags behind at higher speeds; there is less time available for heat transfer to the tunnel structure.

Boosters installed close to the source of the fire can break down due to the radiation produced by the fire, while further downstream from the fire the hot fumes can be the cause of the breakdown. The distance downstream of the fire at which the boosters remain in operation is given by the calculation program developed by the Centre for Fire Safety TNO-Engineering. Since the results of this program have not been validated yet, the following starting points are being taken into account for the moment:

"Large" fire

- All ventilators downstream from the fire within a distance of 300 to 500 m from the fire will break down because of the high temperatures. The temperature of the fumes in this zone reach well above 250 to 300°C, the maximum value for the boosters.
- The radiation effect is not taken into account.

"Medium-sized" fire

- All ventilators downstream from the fire within a distance of 150 to 300 m from the fire will break down because of the high temperatures. The temperature of the fumes in this area reach more than 250 to 300°C, the maximum value for the boosters.
- The radiation effect is not taken into account.

"Small" fire

- The temperatures produced are such that all boosters remain working.
- The radiation effect is not taken into account.

Due to the large number of variables involved, an accurate calculation of the capacity required in the

event of fire is a complicated matter. The result of the calculation stands or falls with the criteria chosen. Because a lot of these criteria are arbitrary it is not a very good idea to make such a detailed calculation. It is better to introduce simplifications and not to try to be comprehensive. By using the current calculation program developed by the Civil Engineering Division a calculation in the event of fire can be made simply but still only for the booster system.

Depending on the gradients in the tunnel and the site of the fire, the ascending effect of the hot fumes must be taken into account: the extent of which is determined by the difference in height and in temperature of the air columns (chimney effect). The ideal situation in this respect is if a fire breaks out in the lowest part of the tunnel because then the column of hot air helps to increase the air flow. If the tunnel exit, however, is lower than the site of the fire, this has a counteractive effect on the air flow. Chimney effects are difficult to calculate and require extensive programming work. The program developed by the Engineering Division does not have these facilities and therefore does not take this effect into account. It is possible that this will be provided for in the future. Anyway this has only a small effect on the final results for Dutch tunnel geometry because the differences in height are small.

Since the volume of air is also determined by the total driving force available, which depends on the temperature of the air, which in turn depends on the volume of air, it is clear that the calculation is iterative and must be made with the help of a computer.

7.11 CALCULATION OF NOISE PRODUC-TION OF BOOSTERS

7.11.1 General

The sound level (L_p) in a space decreases, if the distance between listener and the source increases. Above a certain distance no decrease occurs and the sound level remains fairly constant.

The sound heard consists of:

- direct sound (originating directly from the source)
- indirect sound or reflected sound (by walls, floor, ceiling, etc.)

The extent to which reflection occurs depends on the sound absorbing capacity of the space. In a com-

pletely "hard" space all sound waves are reflected, in a completely absorbing space all sound waves are absorbed (dead space). The total absorption in a space is characterized by the equivalent absorption surface area (A) and expressed in m² of open space

$$A = \sum_{i=1}^{n} \alpha_i A_i$$
(7.39)

where:

- α_i = sound absorption coefficient of material concerned (-)
- A_i = surface area of space limit i under consideration (m^2)

A diffuse sound field is built up in a space where the sound is reflected several times by the walls, ceiling, etc. The sound intensity level resulting from reflections attenuates the direct sound from the source which can result in an increase of the sound level. The sound intensity level in relation to the unrestricted air space increases as the sound absorption of the space becomes smaller. This can be expressed as follows for a cube-shaped space:

Lp = Lw + 10 log
$$\left(\frac{Q}{4 \pi r^2} + \frac{4}{A}\right)$$
 (7.40)

where:

- L_p = sound intensity level of the space in dB in relation to 2 x 10⁻⁵ N/m₂ (dB)
- L_w = sound energy level in the space in dB in relation to 10(dB)

Q = direction coefficient of a radio source (-)

r = distance between listener and source (m)

A = total absorbing surface area of the structure in m^2 of open space (m^2)

According to Sabines law the absorbing surface area of cube-shaped spaces can be determined as follows:

$$A = \frac{V}{6 T}$$
(7.41)

where:

$$V =$$
 volume of the space (m³)
T = reverberation time (s)

The aforementioned theory has been adopted for diffuse sound fields in enclosed spaces and cannot

therefore be used to describe the sound field in a tunnel. The sound produced in a tunnel does not come back in the opposite direction but disappears outside.

A better approach based on a geometric method, the so-called reflection source method, is to calculate the decrease in sound by adding up the contributions made to the sound by the various subsources. This can only be calculated correctly by using a computer. A calculation method which can be worked out manually has been developed for tunnels based on this computer model.

7.11.2 Rough manual calculation model to determine the sound production of ventilators in tunnels

An average sound absorption coefficient in the tunnel is used in the manual calculation method, namely:

$$\overline{\alpha} = \frac{\alpha_{w} \mathbf{x} \mathbf{h} \mathbf{x} 2 + (\alpha_{vl} + \alpha_{pl}) \mathbf{x} \mathbf{b}}{2 \mathbf{x} (\mathbf{h} + \mathbf{b})}$$
(7.42)

where:

α,,	=	sound absorption coefficient of the	
		walls	(-)
α_{vl}	=	sound absorption coefficient of the	
		floor	(-)
$\alpha_{\rm pl}$	=	sound absorption coefficient of the	~ /
		ceiling	(-)
h	=	average height of the tunnel tube	(m)

b = average width of the tunnel tube (m)

The sound level in the tunnel can be calculated roughly from the following derived equation:

$$Lp_i = Lp_{1m} - 20 \times \log r \times (1 - 0.711 \times (1 - \overline{\alpha}_i)^2)$$

(7.43)

where:

- Lp_i = sound intensity level in the tunnel as a result of a sound source on frequency band i, in dB related o 2 x 10⁻⁵ N/m² (dB)
- Lplm = sound intensity level of the sound source at a distance of 1 metre in an unrestricted air space, in Db in relation to 2×10^{-5} N/m² (Db)

 α_i = average sound absorption coefficient of the tunnel tube for frequency band i (-)

The sound intensity level at a distance of 1 metre from the source in the unrestricted air space is determined according to the equation:

$$Lp_{lm} = Lw_i + 10 x \log \frac{Q}{4 \pi r^2}$$
(7.44)

where:

=	sound energy level of the sound source	ce on
	frequency band in dB in relation	
	to 10^{-12}	(dB)
	Ξ	= sound energy level of the sound source frequency band in dB in relation to 10^{-12}

- Q direction coefficient, in the situation in question Q = 2(-)
- distance between the sound source and r = recorder, whereby a distance of 1 metre must be maintained (m)

The total sound intensity level is determined by the adding up the sound intensity levels in terms of energy of each sound source according to the equation:

$$Lp_{itot} = 10.\log (10^{0.1 \times Lpil} + 10^{0.1 \times Lpi2} + 10^{0.1 \times Lpi3} + \dots \text{ etc.})$$
(7.45)
where:

where:

Lptot = the total sound intensity level of all sound sources on frequency band i (dB)sound intensity level at reference point due Lp_{i1} =

to sound source 1, on frequency band(dB) Lp_{i2} sound intensity level at reference point due =

to sound source 2, on frequency band(dB) sound intensity level at reference point due Lp_{i3} = to sound source 3, on frequency band(dB)

The dB(A) value can be determined from the calculated frequency-related sound intensity level according to the equation:

$$Lp_a = -10 \times \log \sum_{i=2}^{10^{-0.1 \times (Lpitot-Ci)}}$$

where:

Lp,	=	total sound intensity level	dB(A)
C _i	=	standard correction term for the	spectrum
		according to the dB(A) filter	(-)

The correction term C_i is:

frequency in H	125	250	500	1000	2000	4000
band i	2	3	4	5	6	7
Ci in dB	16.1	8.6	3.2	0	-1.2	-1

The total inaccuracy of the calculation method is approx. 3 dB(A)

In the case of the deviating tunnel measurements of the Zeeburg tunnel a shape factor B' can be introduced to determine the sound intensity level in the tunnel, i.e.:

$$Lp_i = Lp_{im} -A' + B \tag{7.47}$$

where:

- A' = 20 x log r₁ x $[1 0.711 x (1 \overline{\alpha}_i)^2]$ dB(A)B' = 10,61 x (O_t/A_t) x $(1 - \overline{\alpha}_t)^{-0.05} - 5,76$ dB(A) O_t = circumference of the tunnel tube cross sec-
- (m) tion
- surface area of the cross section of the tunnel A, = tube (m^2)

MEASUREMENTS IN THE ZEEBURG 7.12 TUNNEL

Sound measurements were taken in order to determine the noise level in the Zeeburg tunnel due to the longitudinal ventilation system of boosters.

The results show that the noise levels measured are approx. 1.5 dB(A) lower than the calculated dB(A) values, made according to the method given in 7.11. This small deviation is not discernable within the range of perception and falls within the limits of the accuracy of the calculation method.

(7.46)

8 PROBABILISTIC CALCULATION METHODOLOGY (A. Franken)

8.1 GENERAL

In this chapter of the present guidelines the calculation methodology is modified compared to the one used in the 1975 guidelines. In the previous guidelines a **deterministic** calculation methodology was used, in the present guidelines a **probabilistic** calculation methodology is used. In this chapter it is explained why the probabilistic calculation methodology should be preferred and what the consequences of this are for the new calculation model. This chapter should be seen as the basis for Chapter 9 "Standardization" and Chapter 10 "Probabilistic calculation methodology".

Although an account of the current state of knowledge is aimed at which is as comprehensive as possible, the present design of the probabilistic calculation model can by no means be considered to be completely developed. The present design is, however, more of a good foundation which can be worked out further in the future. Therefore only carbon monoxide is taken into account from the dangerous substances. At present only the "stagnating traffic" and "fire" scenarios have been reasonably completely translated into the new design.

8.2 DESCRIPTION OF THE DETERMINIS-TIC CALCULATIONS METHODOLOGY

Starting with a standard for the concentration of Hb-CO in the blood and a certain scenario, the maximum permissible concentration of CO in the tunnel tube follows depending on the exposure time. On this basis the number of ventilators is calculated, which is a function of different variables, such as tunnel geometry, traffic composition, emission, wind speed, effective ven-tilation capacity, etc. After the values of these variables have been determined, the number of ventilators, which would make the CO concentration in the air lower than or the same as the permissible concentration, is given in the results of the calculations.

By varying the value of the parameters (sensitivity

analysis) the designer can gain insight into the effect of the parameter concerned on the number of ventilators.

8.3 DESCRIPTION OF PROBABILISTIC CALCULATION METHODOLOGY

The difference between the deterministic calculation methodology used in 1975 and the probabilistic methodology which has been followed in the present guidelines, is that a probability of occurrence is assigned to the variation in the value of a parameter. A parameter with a probability distribution is called a stochastic function. By including the probability distributions of the various parameters in the calculation, the end result also has a probability distribution.

The advantage of the probabilistic calculation methodology can be clearly seen, if the limitations of the deterministic design methods are considered.

By attributing a deterministic value to the parameters the designer is often, although not explicitly, using a safety factor (worst case method: for example using an extremely high wind speed for safety reasons or assuming that an escaping motorist will have to walk the *whole length* of the tunnel and the speed at which he walks is estimated conservatively). The inclusion of these safety factors in the calculations has the result that the designer exaggerates dimensions, certainly if more parameters or complicated calculations are involved, but that he has no insight into the safety level or the chance of failure.

In the case of the probabilistic calculation methodology the designer gains explicit information about the chance of occurrence of a certain undesirable situation (failure) from the probability distribution of the results and can include it in the subsequent design.

8.4 **REDEFINING THE PROBLEM**

In the case of deterministic calculations the required volume of fresh air is determined based on the standard for the concentration of Hb-CO in the blood, after which the number of ventilators follow from the calculations. The probabilistic calculation methodology takes the number of ventilators as the starting point, after which the probability distribution of the concentration of a substance X in the blood is determined for a given tunnel geometry and scenario.

The following arguments are applicable to this redefinition:

- the probability distribution of "the concentration of a substance X in the blood" is more useful than a probability distribution of "the number of ventilators in the tunnel"
- a probability distribution of the concentration can be tested against the existing VROM guidelines, so that the safety of the tunnel can be given a foundation
- besides the probability distribution of the concentration of substance X in the blood the probability distribution of other relevant variables, such as air speed in the tunnel and concentration of substance X in the air, can also be determined
- by taking the number of ventilators as the starting point the different scenarios can be compared properly.

The consequence of this redefinition is that the number of ventilators has to be determined iteratively.

As the number of parameters with a probability distribution is increasing and the complexity of the calculations is also increasing, computer programs must be resorted to for reasons of efficiency. Since its existence in 1985 the Hydraulic Engineering Department of the Civil Engineering Division has been active in the area of probability as a part of risk analysis. To carry out risk analyses the Hydraulic Engineering Department has developed several standard programs for carrying out probabilistic calculations. One of these programs, the Probvent program, has served as a basis for the probabilistic tunnel ventilation program.

8.5 DESIGN OF PROBABILISTIC CAL-CULATION MODEL

In this paragraph the probabilistic calculation model is explained in broad outline. For a detailed description of the model refer to Chapter 10. If the concentration of, for example the substance X in the blood is specified by Y, Y can be expressed as a function of various basic parameters:

Y = f (number of traffic lanes, tunnel length, percentage goods vehicles, traffic speed, wind speed, wind direction, emission, exposure time, etc.)

Several of these parameters, such as the number of traffic lanes, have a deterministic character, others, such as wind speed and wind direction in contrast have a stochastic character. How many and which parameters are included as stochastic is determined by among other things:

- the available and desirable calculation time
- the distribution of the parameter in question
- the sensitivity of the end result to variations in the parameter value
- state of the technology

A value is given to the deterministic parameters by means of an input model and the probability distributions of the stochastic functions are determined. By using the Probvent program a full numerical integration is subsequently carried out of the probability density function of all the stochastic functions. By calculating the value Y for every combination of possible values of the stochastic functions, the probability distributions of the various variables are presented in a way which gives insight to the user.

9 STANDARDIZATION (A. Franken)

9.1 GENERAL

This chapter deals with the necessity to standardize and gives various standard values for the probabilistic approach.

The deterministic calculations are based on permissible values which are used as an absolute limit. This limit is prevented from being exceeded by means of a safety margin. In the probabilistic method this permissible value is no longer absolute but a permissible probability is given to exceeding this limit.

In addition, standardization is limited to the situation *in* the tunnel tube. Standards with respect to the surroundings of the tunnel are not dealt with in this chapter but in Chapter 6 "Permissible levels of air pollution".

As already stated in the introduction to Chapter 8 the probabilistic calculation method for the tunnel ventilation model is still at the developmental stage. Standardization has only been completed for carbon dioxide (CO). The other dangerous substances may be dealt with at a later stage.

9.2 NECESSITY FOR STANDARDIZATION

A probability distribution of a result is not sufficient in itself. In order to know if a chance of a failure occurring is small enough, a standard must be defined to which this chance of failure can be compared.

The resulting standard consists of two elements:

- a standard value being a maximum permissible value

- an accepted chance of exceeding this standard value

The (accepted) chance of exceeding the standard is therefore given to the event.

In formulating the standards for tunnel ventilation connections are tried to be found as much as possible with the existing standards and generally accepted risk levels.

9.3 PHILOSOPHY

9.3.1 Starting points

In these guidelines the following scenarios with variables which are determinative for design are used:

– stagnating traffic:	CO concentration/
	deterioration in visibility
- emergency assistance:	CO concentration/
	deterioration invisibility
- escaping motorist:	CO concentration
– fire:	minimum volume of air
	required

Two philosophies are followed based on these scenarios:

9.3.2 Health philosophy

The "stagnating traffic" and "emergency assistance" scenarios are situations which occur relatively frequently for the people concerned. For this reason the standard is determined from a health point of view which is related to the guidelines of the Department of Public Housing, Physical Planning and the Environment (VROM), see Chapter 6, Table 6.1.

These guidelines give an average value per hour of 40 mg/m^3 as the limiting value for CO concentration in the air which may be exceeded 0.01% of the time.

For the time being the data presented in Table 6.1 are taken as a basis although the data in Table 6.4 could also be used. The consequence of this is that the standard chosen is on the safe side.

9.3.3. Safety philosophy

The "escaping motorist" and "fire" scenarios concern exceptional situations. The standards for these situations are therefore determined from a safety point of view.

The health/safety aspect must be guaranteed for every individual taking into consideration:

- differences in sensitivity to the substances between individuals
- the annual time spent by an individual in a tunnel
- the fact that an individual can take part in more than one scenario.

In the following paragraphs the standards are worked out in more detail.

9.4 STANDARDIZATION OF "STAG-NATING TRAFFIC" AND "EMER-GENCY ASSISTANCE" SCENARIOS

9.4.1 Hb-CO standard value

If a person with a relatively low CO background concentration is exposed for an hour to the VROM limiting value of 40 mg/m³, this results in the case of intensive physical effort (work) in a Hb-CO concentration of 5.7% in the blood (see Appendix A).

In the "emergency assistance" scenario the length of time is limited to 1 hour and the activity of the member of the emergency service is "working". For the "stagnating traffic" scenario the duration of the stay in the tunnel depends on the speed of the traffic and the length of the tailback.

Since both scenarios occur reasonably frequently a standard value of 5% Hb-CO in the blood is adhered to from the health risk point of view.

9.4.2 Probability of exceeding limits

Based on the VROM standards the standard value of 5% Hb-CO in the blood may be exceeded 0.01% of the time.

The length of time that the standard value may be exceeded is not significant to the problems concerning ventilation but the chance that this may happen while passing through the tunnel is. Therefore it is necessary to convert the "standard of time" into the "tunnel-journey standard". The problem with this is that the percentage of the total duration of the time which may be spent in the tunnel if the standard value is exceeded is not known. Because of this uncertainty only the range can be given within which the permissible probability of exceeding the standard value must lie for every journey through the tunnel.

A lower limit for the probability of exceeding the standard value for each journey through the tunnel can be estimated by supposing that the duration of the stay in the tunnel is just as (un)healthy as the time spent at another location chosen at random. This means that exceeding the standard value 0.01% of the time also applies to the duration of the stay in the tunnel. The lower limit is therefore not related to the scenario.

An upper limit for the probability of exceeding the Hb-CO standard value can be estimated by supposing that the time spent in the tunnel is the normative situation for the average permissible CO concentration per hour, according to VROM. This means that the *total* length of time of exceeding the standard value is spent in the tunnel. The upper limit of the probability of exceeding the standard value therefore depends on the time spent in the tunnel and thus differs for each scenario.

9.4.3 Probability of exceeding the standard value in the "stagnating traffic" scenario

The chance of exceeding the Hb-CO standard value for each journey through the tunnel is given in equation (9.1):

$$P_{CO} \ge n_t \ge t_t < T_{CO} = P_{CO} < T_{CO}/(n_t \ge t_t)$$
 (9.1)

where:

P _{co}	= chance of exceeding the Hb-CO	
	standard value for each journey	
	through the tunnel	(-)
n,	= number of journeys through the	
-	tunnel per annum	(lj)

- t₁ = duration of a journey through the tunnel (h)
- T_{co} = time per annum that the Hb-CO standard value may be exceeded in the tunnel (h/j)

A commuter who travels every day through a tunnel, in the morning as well as in the evening, is taken as the starting point for the "stagnating traffic" scenario. The number of times travelled through the tunnel amounts therefore to approx. 500 per annum. It is assumed that in 20% of the cases the commuter encounters stagnating traffic in the tunnel, so that the number of times travelled through the tunnel with stagnating traffic (n_0) amount to approx. 100 per annum.

Assuming an average speed of 6 km/h in stagnating traffic it applies to one a journey through a tunnel L m long that:

$$t_t = L \times 10^{-3}/6$$
 (h)

For the lower limit of the chance of exceeding the HbCO standard value a time of exceeding the annual time spent in the tunnel of 0.01% applies. From this it follows that:

 $t_{min} = 10^{-4} x n_t x t_t$ so that for $P_{CO, min}$ it applies to each journey that:

$$P_{\infty, \min} = 10^{-4}$$
 (9.2)

The upper limit of the chance of exceeding the Hb-CO standard value for each journey is determined by stating that:

$$T_{CO,max} = 0.8766$$
 hour (0.01% of 8766 h/y),

therefore it follows that:

 $P_{CO,max} < 0.8766/100 \text{ x L x } 10^{-3}/6)$ and thus: $P_{CO,max} = 5 \text{ x } 10^{-2}/\text{L x } 10^{-3}$

9.4.4 Chance of exceeding standard value in the "emergency assistance" scenario

(9.3)

It appears from accident statistics that the number of accidents in the most important tunnels in the Netherlands is about 30 per tunnel per annum. If it is assumed that emergency assistance is required in all accidents and that for each tunnel emergency service work is ensured by 4 shifts working continuously, this means that each member of the team will be called into action approx. 8 times a year.

The time spent in the tunnel by the emergency service personnel is set at a maximum of 1 hour. In practice the tunnel tube is closed off in the event of blockages lasting a longer period of time.

The upper limit for the chance of exceeding the standard value for each emergency service action is given by equation (9.4):

 $P_{CO, max} < 0.8766/(100 \times 10^{-3}/6)$ (9.4)

and the lower limit:

 $P_{\rm CO,\ min} = 10^{-4} \tag{9.5}$

9.4.5 Standard value for deterioration in visibility

Although the volume of smoke in the tunnel air is a determinative factor for comfort and good visibility, a health risk is also associated with breathing in smoke particles. In view of the fact that the extent of this is not well-known, the standard value employed by the PIARC is adopted. This recommendation assumes a light transmission of T over a distance of 100 m. This results in an acceptable k value, which is different for the speed ranges 0-40 km/h and above 40 km/h.

The acceptable levels are as follows:

v < 40 km/h: T _{100m} = 40% \rightarrow k_{max} = 4 x 10⁻³ m⁻¹

v < 40 km/h: T _{100m} = 48% \rightarrow k_{max} = 3.2 x 10⁻³ m⁻¹

9.5 STANDARDIZATION OF "ESCAPING MOTORIST" SCENARIO

9.5.1 Hb-CO standard value

From the safety point of view it is supposed that the percentage Hb-CO in the blood must be low enough that it does not hinder escape from the tunnel. For this reason the standard value of 10% for the percentage Hb-CO in the blood after exposure is adhered to. This value will not be a problem for the majority of motorists. It is accepted that people with a heart condition will feel pain. Since this situation only crops up in disasters, it is considered acceptable.

9.5.2 Chance of exceeding standard value

In general an escape situation will arise in the event of a blockage of the tunnel tube as a result of a (large) accident. This is for example the case if an accident occurs in the tunnel tube in which a goods vehicle turns over.

It is reported in the literature that in each tunnel approx. 3.33 accidents occur every year in which a goods vehicle is involved. The same sources indicate that the probability, given that an accident has occurred, that a goods vehicle turns over is 0.0045.

Therefore the chance of an escape situation arising is:

P (escape situation) =3.33 x 0.0045
=1.5 x
$$10^{-2}$$
/year (9.6)

Exceeding the standard value of 10% Hb-CO in the blood during the escape is undesirable but does not directly give rise to a life-threatening situation. This can indeed be the case, if besides exceeding the standard value other failure mechanisms occur, such as fainting, no help from bystanders, suffocation, etc.

In view of the consequences the chance of exceeding the standard value during an escape situation is set at a relatively low level of:

$$P (Hb-CO) > 10\%$$
 | escape situation) < $10^{-2}(9.7)$

9.6 STANDARDIZATION OF "FIRE" SCE-NARIO

9.6.1 Standard value for air volume/speed

It is assumed that the number of casualties resulting from a serious accident or a disaster, in which a "large" fire breaks out, is 40. This number is caused by the accident itself and by the fire. Several casualties die because they are not in a state to escape due to the fact that they are trapped or unconscious or cannot get away for other reasons. These people could still have been rescued, if a fire had not broken out. The ventilation system does not have any effect on the number of these casualties.

The ventilation system can only limit the consequences of the disaster by ensuring that the stranded motorists are not exposed to the hot combustion gases and emergency assistance can be effected. In addition the ventilation system must ensure the supply of adequate combustion air and complete combustion. The most important requirement in the event of a "large" fire is that the ventilation system must achieve a minimum air flow rate of 88 m³/s in the tunnel tube. This supply of air must ensure that there is an air flow over the source of the fire in the direction of the the exit so that the hot combustion gases are discharged from this side of the tunnel. This output rate, which is in line with an air speed of approx. 1.5 m/s in a 3-lane tunnel tube is necessary to prevent the danger of explosion arising.

9.6.2 **Probability of going below the standard** value

Methodology

It is assumed that going below the minimum air flow rate of 88 m³/s will result in an explosion. Due to the fact that the tunnel will collapse completely if this happens, the number of casual-ties increases by a factor of 15, from 40 to about 600. Experience shows that in the event of an accident with more casualties at the same time, the size of the group should be taken into consideration.

In the Netherlands there are two schools of thought concerning risk analysis, namely the VROM standardization and the standardization formulated by the Technical Advice Committee for Dykes and Dams (TAW) which is more in line practice. Although both underlying with philosophies do not agree with each other on several basic points, they calculate the group risk in the same way. In the TAW as well as in the VROM calculation of the group risks it is assumed that the probability of several casualties must be inversely proportional to the square of the number of possible casualties:

$$P: 1/n^2$$
 (9.8)

where:

$$P = chance of several casualties (-)
 $n_s = number of possible casualties (-)$$$

Working-out

If during a large fire the minimum air flow rate is not realized there is a high probability of an explosion occurring and the number of casualties will increase, as indicated above, by a factor of 15. This means that the probability of this happening must be smaller by a factor of 15^2

Therefore equation (9.9) applies to the acceptable probability of going below the minimum air flow rate during a "large" fire as follows:

$$P(Q_t < 88 \text{ m}^3/\text{s} | \text{fire}) = 1/15^2 < 5 \text{ x} 10^{-3}$$
 (9.9)

Or in other words:

Of the 200 times that a fire breaks out in a tunnel, the 88 m^3 /s value may only be gone below 1 time.

Application

Up to the present time hardly any data are known about a "medium-sized" to "large" fire breaking out in a tunnel tube or on a motorway so that no useful standards can be set for these events at the moment.

With respect to a "large" fire breaking out the data for a "medium-sized" fire with a tanker are adopted. The chance of a "medium-sized" fire in the event of an accident with a goods vehicle laden with a flammable liquid (petrol) is 4.5 x 10^{-3} . With an normative accident frequency of 2 x 10^{-7} per vehicle kilometre this means a probability of fire of $9x10^{-10}$ per vehicle kilometre. The number of vehicle kilometres of goods vehicles with flammable loads is 7.35 x 10^4 so that the probability of a large fire occurring in a tunnel per annum is expressed by equation (9.10):

P(fire) =
$$7.35 \times 10^4 \times 9 \times 10^{-10} = 6.7 \times 10^{-5}$$
 (9.10)

The probability of a "large" fire occurring which leads to an explosion with about 600 casualties follows from equations (9.9) and (9.10) and is given in equation (9.11):

P (casualties) = P (large fire) x P ($Q_t < 88 \text{ m}^3/\text{s}$) = 6.7 x 10⁻⁵ x 5x10⁻³ = 3.5 x 10⁻⁷

9.7 CONCLUSION

The normative standard values to be used are given in Table 9.2 with the probabilities of ex-ceeding and going below these standard values.

In view of the assumptions which underlie the determining of the above-mentioned probabilities of exceeding and going below the standard values, these values do not apply as absolute guidelines but are more of an indication for the safety of the ventilation system. The designer himself will have to estimate, if the probability realized of the extent of exceeding and going below the standard values provides sufficient safety.

Finally it applies that the above-mentioned probabilities of exceeding and going below the standard values are based on Dutch standards concerning health and group risk. In other countries other values can apply to the standard values and probabilities.

scenario	standard value	probability per event
stagnating traffic	Hb-CO < 5%	$< 10^{-4}$ à 5 x $10^{-2}/L$ x $10^{-3}*$
emergency assistance	Hb-CO < 5%	$< 10^{-4} \text{ à } 10^{-1}$
escaping motorist	Hb-CO < 10%	< 10 ⁻²
large fire	$Q_t < 88 m^3/s$	$< 5 \times 10^{-3}$

TABLE 9.2:

Probabilities of exceeding and going below the standard values

* L = tunnellength

10 CALCULATION PRINCIPLE FOR LONGITUDINAL VENTILATION ACCORDING TO THE PROBABILIS-TIC CALCULATION METHOD (A. Franken)

10.1 GENERAL

This chapter deals with the probabilistic calculation method for longitudinal ventilation stems as used in these new recommendations.

10.2 DETERMINATION OF THE AIR SPEED IN THE TUNNEL

The calculation principle for longitudinal ventilation is described in Chapter 7.

10.3 DETERMINATION OF THE Hb-CO CONTENT IN THE BLOOD

10.3.1 Introduction

The way in which the concentration of Hb-CO in the blood can be determined is explained in this section. Using the calculated air quantities and the CO emission produced by traffic as a basis, the CO concentration in the tunnel is determined first. The duration of the stay for each tunnel user and the resulting Hb-CO concentration in the blood are subsequently calculated. The factors required to determine the Hb-CO concentration in the blood are dealt with consecutively.

10.3.2 Determination of Hb-CO concentration in the blood

May's graphs given in Appendix A show the relationship between the Hb-CO percentage in the blood with the CO concentration of the inhaled air, the exposure time and the activity. These graphs are also used by the Health and Safety Inspectorate.

The relationships which May gives are expressed in the following equation:

Hb-CO = 0.011 x
$$C_{\infty}^{0.79}$$
 x $T_{stay}^{0.65}$ (10.1)

where:

The absorption of CO in the blood as well as the CO concentration in the inhaled air are also determined by the exposure time and the activity carried out. Thus according to May the speed of absorption of CO by the human body during the activity "walking" and "working" is 2 and 3 times faster, respectively, than during the activity "resting".

This effect is calculated for the activities "walking" and "working" by multiplying the duration of the stay by a factor of 2 and 3, respectively. Thus 10 minutes "walking" or "working" correspond to 20 and 30 minutes "resting", respectively.

10.3.3 CO production

Given a certain percentage of goods vehicles and a certain traffic speed and by using the "Traffic lane composition" given in Chapter 4, the number of vehicles per category in the tunnel can be determined. Based on the relationships formulated by the Institute for Road Transport TNO in Chapter 3 "Exhaust fume emissions", the total CO production in the tunnel tube can then be calculated from:

$$E_{CO, \text{ tot}} = \sum_{\text{cat.1}}^{\text{cal.9}} (n_v \cdot E_{CO, v})$$
 (10.2)

where:

= total CO emission in the tunnel	
tube	(g/h)
= number of vehicles of 1 category	in the
tunnel tube	(-)
= CO emission per vehicle	(g/h)
	 = total CO emission in the tunnel tube = number of vehicles of 1 category tunnel tube = CO emission per vehicle

In the determination of the total CO production the fact that the emission values in Chapter 3 are given in grams per hour must be taken into account.

10.3.4 CO concentration in the tunnel tube

In a longitudinal ventilation system the concentration of carbon dioxide increases linearly: from an initial concentration $C_{CO, entrance}$ at the entrance to a concentration $C_{CO, exit}$ at the exit, in which

$$C_{CO exit} = C_{CO, entrance} + E_{CO, tot} / (u_t \times A_t)$$
(10.3)

If no recirculation effects occur, it is possible to give a surrounding area value to $C_{CO, entrance}$ of approx. 17.4 mg/m³ (15 ppm). In the event of recirculation a considerably higher value will apply. It has been shown from research on recirculation problems that without taking supplementary measures to prevent short circuiting in certain wind conditions, recirculation percentages can be expected of 30 to 40%. This means that 30 to 40% of the out flowing tunnel air is sucked in by the adjacent tunnel tube. By taking appropriate measures this percentage can be reduced to 5 to 10%.

The determination of the Hb-CO percentage in the blood is based on an average CO concentration during the exposure. This depends on the type of scenario:

Stagnating traffic

It is assumed that the motorist travels through the tunnel tube at a uniform speed. Therefore it applies to this scenario that:

$$C_{CO,gem} = (C_{CO, entrance} + C_{CO, exit})/2$$
 (10.4)

Emergency assistance

The concentration which an emergency service worker encounters is determined by the place in the tunnel tube where he is working. If this place is indicated as a fraction "f" of the length of the tunnel from the entrance opening, then the average CO concentration to which the emergency service worker is exposed is expressed by equation (10.5):

$$C_{CO, avgc} = C_{CO, cntrance} + f x$$

$$(C_{CO, exit} - C_{CO, entrance}) \qquad (10.5)$$

Escaping motorist

The escaping motorist will escape from a certain place in the tunnel tube in the direction of the entrance. The average concentration to which the escaping motorist is exposed is determined by the escape route which he must take. If the escape route is indicated as a fraction "f" of the length of the tunnel, assuming a constant escape speed, the average CO concentration for the escaping motorist is expressed in equation (10.6):

$$C_{CO}, avge = \{C_{CO}, entrance + f x \\ (C_{CO, exit} - C_{CO, entrance})\}/2$$
(10.6)

where:

f = fraction of the length of the tunnel over which the motorist escapes; $0 < f \le 1.0$

An waiting effect was taken into account in the last recommendations made in 1975 whereby the motorist waits before deciding to leave the tunnel. No foundation for this waiting time can be given. In Chapter 2, section 2.4.3 it is proposed that a waiting time of 10 minutes before the motorist decides to escape is adopted. Since it is not definite how long this waiting period actually is, it was decided not to include the effect of the higher CO concentration during waiting in the determination of the average concentration. In the event of serious disasters, which are being discussed here, it is uncertain how the public will react.

Besides which in most tunnels escape routes are provided with separate escape corridors so that there is no reason at all in this situation to discuss this waiting period. However, in tunnels with an escape route no account is taken of this facility in the framework of the ventilation calculation. It is uncertain to what extent the public will make use of this facility. Therefore it is assumed that the escape will proceed according to the above-mentioned scenario.

10.3.5 **Duration of stay**

Stagnating traffic

For stagnating traffic the duration of the stay in the tunnel is given by:

$$\Gamma_{\rm stay} = 60 \text{ x L/}(1000 \text{ v}_{\rm y}) \tag{10.7}$$

where:

T _{stay}	= duration of stay in the tu	innel tube in
	minutes "resting"	(min.)
L	= length of the tunnel	
	tube	(m)
v,	= speed of the traffic	(km/h)

An exponential distribution is used with the following specific values for the average speed of the traffic when travelling in stagnating traffic or a traffic jam:

TABLE 10.1:

Probabilities of exceeding and going below the speed

speed vv (km/h)	probability of exceeding speed (-)	probability of going below speed (-)	
2	1	0	
6	0,95	0,05	
30	0	1	

The distribution function associated to this is:

(10.8)

P (v < v_v) = 1 - exp
$$\left(-\left(\frac{v_v - 2}{10,9}\right)^{2.95}\right)$$
 (10.8)

The speed travelled in stagnating traffic is always more than 2 km/h and less than 30 km/h. In addition it can be concluded from Table 10.1 that in 95% of cases the speed is higher than 6 km/h and that the speed is lowe only in 5% of cases.

The motorist's activity is "resting".

Emergency service help

The time spent in the tunnel by the emergency service personnel is set at a maximum of 1 hour because in practice it is shown that in the event of blockages lasting for a longer time, the tunnel tube is closed to traffic.

The activity of the emergency service worker is "working" so the time spent in the tunnel in minutes "resting" is:

$$T_{stay} = 3 \times 60$$
 (10.9)

Escaping motorist

In contrast to what has been said in 10.3.4 about not including the higher concentration at the place where the motorist waits, a waiting period of 10 minutes before the motorist decides to walk out of the tunnel is assumed for safety reasons to determine the time spent in the tunnel. It is assumed that the speed of an escaping motorist is 3 km/h, whereby the applicable activity is "walking".

The time spent in the tunnel for the escaping motorist is, just like the average concentration determined by the length of the escape route, expressed as a fraction of the tunnel length. Therefore the time spent in the tunnel is:

$$T_{stay} = 10 + 2 x (f x L/3) x (60/1000) (10.10)$$

10.4 DETERMINATION OF VOLUME OF AIR REQUIRED DURING A "LARGE" FIRE

The volume of air required in the tunnel is determined by:

$$Q_t = u_t \times A_t \tag{10.11}$$

where:

Q		= air flow rate in the tunnel tube	(m³/s)
u	=	average air speed in the empty	tunnel
		tube	(m/s)
A,	=	surface area of the cross section	of the
-		tunnel tube	(m ²)

The determination of u_t follows directly from (7.35). However, the following effects must be allowed for:

- 1. It is assumed that during the "large" fire all the ventilators break down downstream of the fire in a tunnel 300 to 500 m long. As a result of which the number of ventilators contributing to the ventilation declines.
- 2. The traffic is only stationary in the tunnel upstream from the fire. Away from the site of the fire the tunnel tube is completely clear so that resistance due to traffic only has to be included for a limited length of the tunnel. In addition stationary traffic ($u_t = 0$ m/s) must be taken into account to determine C_w traffic.
- 3. The decrease in the density of the tunnel air and the resulting increase in the air speed downstream from the fire.
- 4. Increased exit losses and increased wall friction due to higher speed.
- 5. Decrease in the capacity of the boosters due to the lower density of the fumes.

10.5 PROBABILISTIC CALCULATIONS

10.5.1 Introduction

Paragraphs 10.2 and 10.3 describe the methodology, given a series of input data to determine the air speed in the tunnel tube and the Hb-CO concentration in the blood.

It has already been stated in Chapter 8 that various input parameters and probability distributions are considered in a probabilistic approach to the problem. As a consequence of which the results of the calculations (in this case u_t and the Hb-CO concentration) also have a probability distribution.

The Probvent program makes it possible, for a given problem, to carry out a full numerical integration of the probability distributions of the stochastic functions. The newly developed tunnel ventilation model is based on the use of this program.

10.5.2 Example

By way of illustration the "escaping motorist" scenario is considered in more detail, in which the wind direction, the wind speed and the fraction of the escape route are taken as the stochastic functions.

The probability distribution of the wind is based on the wind distribution for the meteorological station at Schiphol and is given in Appendix C. The wind is classified into 12 directions (horizontal axis) and 29 speed ranges (vertical axis). The tunnel is assumed to be divided into 10 sections of equal length for the purpose of making a probability distribution of the fraction of the escape route.

The probabilistic tunnel ventilation program formulates sets of input data for all the possible situations which can occur. At a given wind direction and wind speed there are 10 different situations possible because of the variation in the fraction of the escape route. By also varying the wind direction and the wind speed the number of possible situations increases to 12 x 29 x 10 =3480(!). For each of these situations the probability of occurrence and the resulting Hb-CO concentration in the blood is determined.

Take for example the situation that at a wind speed of 10 m/s coming from an easterly direction a motorist at 0.8 times the tunnel length is forced to escape. From Appendix C it follows that this wind has a probability of occurring of 135×10^{-5} . With a uniform distribution of the escape situation along the tunnel length the probability that the escape route is $0.8 \times L$ is 0.10. The resulting probability of the above situation occurring is therefore 135×10^{-6} . The set of input data in the tunnel ventilation model now consists, in addition to data on the traffic, tunnel and ventilation, of the parameters $u_{wind} = 10$ m/s, wind direction = 90° C and f = 0.8. Without going into the calculation in any more detail it is reported that the above-mentioned situation leads to a Hb-CO concentration in the blood of 12%.

All possible (3480) situations are worked out in this way, in which the percentage Hb-CO is determined as well as the probability of occurrence of such a situation. By for example adding up all the probabilities of occurrence of situations resulting in a Hb-CO percentage of 12%, the total probability of a percentage Hb-CO of 12% is obtained. If the same is done for all situations resulting in a Hb-CO percentage greater than 10%, the probability of exceeding the standard in the "escaping motorist" situation is obtained.

10.5.3 **Description of model**

The large number of situations which must be worked out makes the necessity of the numerical approach clear. For this reason the Hydraulic Department together with the Tunnel Engineering Department of the Civil Engineering Division of the Directorate-General for Public Works and Water Management have designed a numerical model.

The model, which is based on the probabilistic Probvent program, offers the possibility of determining the consequences of a chosen longitudinal ventilation capacity in a deterministic as well as a probabilistic way.

The following aspects are included in the calculation:

- the length and width of the tunnel
- the orientation and position of the tunnel openings (whereby a possible curve can be allowed for)
- the composition of the traffic and average travelling speed
- the CO and smoke production of the traffic
- the car resistance
- the direction-related wind speed and wind pressure coefficient
- the efficiency of the ventilation system
- the duration of the stay of a tunnel user
- the outside air concentration or the recirculation percentage
- the reversibility of the system in the case of stagnating traffic.

The number of ventilators can be given as several ventilators which are installed in groups near the entrance opening, plus several ventilators which are evenly distributed along the length of the tunnel.

The following aspects have not been included in this version (May 1991) of the model:

- the production of substances other than CO and smoke
- the possibility of two-way traffic in the tunnel tube
- a variable tunnel cross section
- the possible reversibility of the ventilation system
- the lower density of the fumes away from the source of the fire.

How many and which parameters are included as stochastic functions is determined by:

- the calculation time available (each new stochastic function multiplies the number of calculations)
- the possible range of the parameter value
- the sensitivity of the final result to the range of the parameter value
- the state of the technology with respect to describing the phenomenon.

The following parameters have been inputted as stochastic functions in the model (May 1991 version):

- wind speed
- wind direction
- speed of the traffic
- site of the fire
- place of emergency service help
- length of the escape route.

The variables calculated in the program are:

- the air speed and the flow rate in the tunnel
- the CO concentration in the tunnel
- the Hb-CO concentration in the blood of tunnel users
- the deterioration in visibility.

These output variables are presented in graph form. Some examples of this graphical output are included in Appendix E.

10.6 PROBABILISTIC GUIDELINES TRANSLATED INTO DETERMINISTIC GUIDELINES

10.6.1 Introduction

Making probabilistic calculations to determine the number of ventilators in a tunnel is not an easy matter. For design practice to actually be able to make use of the probabilistic model to calculate the best possible ventilation system, it is feasible to translate the outcome of the probabilistic model into a deterministic calculation. Several graphs have been made for this with which a reasonable estimate of the number of ventilators can be made. It should be noted that the design rules only have limited validity. All the conditions set in 10.6.2 "Starting points" must be fulfilled. These starting points have been set as generally as possible. It is not possible to make calculations beforehand for all the situations which occur in practice. If the number of ventilators is determined on the basis of other starting points, then the probabilistic calculation model of the Civil Engineering Division of the Directorate-General for Public Works and Water Management should be

used. Although the manual method gives a reasonable estimate of the number of ventilators, it is advisable that the definitive number of ventilators is eventually determined by the computer program in order to obtain an optimum result.

No manual calculation is presented for the other scenarios as is stated in Chapter 2 because the calculations show that the "large" fire is the normative situation for tunnels up to 1500 m long.

10.6.2 Starting points

The standard for the "fire" scenario (see Chapter 9) is:

P (Q < 88 m³/s | fire) < 5 x
$$10^{-3}$$
 (10.12)

Or in words: the probability that during a "large" fire the volume of ventilation air is smaller than $88 \text{ m}^3/\text{s}$ may not be larger than 1 in 200, or in other words: the standard value of $88 \text{ m}^3/\text{s}$ may only be exceeded 1 time out of the 200 times of there being a "large" fire in the tunnel.

The graphs are based on the following basic points:

1. Ventilation system

The following ventilators are used:	
Exit output flow rate	12.5 m ³ /s
Exit speed	40.0 m/s
Output of system	0.75

Some of the ventilators are installed at the beginning of the tunnel and some along the tunnel. The ratio of the number of ventilators in the two positions should be determined by the designer.

2. Composition of the traffic

Percentage goods vehicles 15%.

The goods vehicles and the cars are divided into different categories:

Goods vehicles (per cent of the number of goods vehicles):

-	light goods vehicles	(HD1) 33.3%
-	medium-heavy goods	
	vehicles	(HD2) 33.3%
-	heavy goods vehicles	(HD3) 33.3%

Cars (per cent of the number of cars) - cars (1504) 25.0%

-	cars	(US'83)	25.0%
-	cars	(diesel)	25.0%
	vans	(15-04)	10.0%
-	vans	(US'83)	5.0%
-	vans	(diesel)	10.0%

- 3. Resistance factors
 - The model of the wind effect is as described in Appendix D.
 - Car resistance.

The following values are adopted for the resistance of all goods vehicles and cars:

category	Cw (-)	A⊥ (m2)		
goods vehicles	1,0	6,5		
cars	0,55	2,0		

- For the inflow and outflow losses a combined factor of 1.2 is used (tunnel without grid).
- The friction coefficient for the tunnel walls is 0.016.
- 4. Tunnel geometry
 - Straight tunnels are assumed.
 - For two traffic lanes the surface area of the cross section of the tunnel is 50 m^2 and the circumference is 30 m.
 - For tunnels up to 1500 m long it applies that the "large"
 - fire scenario is the normative situation.
 This design method is therefore applicable to tunnels which are less than or are 1500 m long.

10.6.3 Calculation method

The following parameters are required for the calculation:

- 1. Total length of the tunnel
 - The number of ventilators at the beginning of the tunnel, for four lengths of the tunnel, are plotted against the number of ventilators distributed along the tunnel in such a way that the standard

for the "large" fire is complied with precisely. In determining the number of ventilators the number should be rounded up. A linear interpolation should be made for lengths other than those cited here. The number of ventilators near the entrance opening is represented in the graphs by V1 and the ventilators distributed along the tunnel by V2.

2. Roughness factor of the surrounding area to convert the wind speed at the measurement point (Schiphol) to the tunnel

Roughness factors for the surrounding area between 0.8 and 1.2 are considered. The coefficient which is given in the graph must be used for the ventilators at the beginning of the tunnel as well as for the ventilators distributed along the tunnel! See the example in 10.6.4 for more information.

3. The orientation of the tunnel

A coefficient is also calculated for the orientation of the tunnel. The same applies to this as to the roughness factor. The orientation of the tunnel is determined by the direction of the traffic and is defined as the direction from which the traffic comes. For this North is 0° . (A tunnel in which cars travel from west to east therefore has an orientation of 90°).

4. The number of traffic lanes in the tunnel

The calculations have been made for tunnels with two traffic lanes. For three traffic lanes the number of ventilators must be multiplied by a factor of 1.2. This applies to the ventilators installed at the beginning of the tunnel as well to those which are distributed along the tunnel.

10.6.4 Example

tunnel section	length (m)	gradient percentage (%)
1	300	-2,0
2	300	-1,0
3	300	3,0

Assume that the tunnel has the following geometry

The orientation is 40° and the surrounding area factor is 1.05.

In a tunnel with two traffic lanes: Determination of the coefficients:

Figure 10.1: The surrounding area factor 1.05 gives a coefficient of 1.10 Figure 10.2: The orientation 40° gives a coefficient of 1.05

coefficient environment factor



FIGURE 10.1: Graph of surrounding area factor

The total correction coefficient of 1,155 is found by multiplying the two coefficients extrapolated from the graphs.



FIGURE 10.2: Graph of orientation

6 ventilators can be installed at the beginning of the tunnel: 6/1.555 = 5.19 ventilators.

This number is then looked up in the graphs for 500 m and 1000m (Figure 10.3):

- 500 m : 14.8 ventilators distributed along the length of the tunnel
- 1000 m : 10.8 ventilators distributed along the length of the tunnel

This means 11.6 ventilators for the total length of the 900 m.

Multiplying by 1.155 gives 13.4, therefore 14 ventilators.

Tunnellength = 500 m



Tunnellength = 1000 m





- v1 = number of ventilators near the entrance opening
- v2 = number of ventilators distributed along the length of the tunnel

Figure 10.3: Graphs on tunnel length

Result: 6 ventilators at the beginning and 14 distributed.

In a tunnel with three traffic lanes:

The difference between a two-lane and a three-lane tunnel can be expressed by a factor. This factor depends on the coefficients and starting points chosen. For the coefficients and starting points stated in this section the factor for a tunnel with three traffic lanes is 1.2. In Chapter 11 in 11.6.3 it emerges that the number of traffic lanes has almost no effect on the number of ventilators.

The procedure is as described above:

 $6/(1.155 \times 1.2) = 4.33$

- 500 m : 16.5 ventilators distributed along the length of the tunnel
- 1000 m : 11.5 ventilators distributed along the length of the tunnel
- 900 m : 12.5 ventilators distributed along the length of the tunnel

 $12.5 \times 1.155 \times 1.2 = 17.3$ therefore 18 ventilators.

Result: 6 ventilators at the beginning and 18 distributed.

If the program is used to check for fire the probability of going below the standard value is:

- two traffic lanes:

 $P(Q < 88 \text{ m}^3/\text{s} | \text{fire}) = 3.8 \text{ x } 10^{-3}$

- three traffic lanes: P(Q < 88 m³/s | fire) = 3.8×10^{-3}

The standard is 5 x 10^{-3} , thus the number of ventilators complies with the standard.

11 CALCULATION EXAMPLES (L. Swart)

11.1 GENERAL

Several examples are given to clarify the new method and in addition to explain the effect of the different parameters on the design. The Zeeburg tunnel is used as an example to find a connection with the practical situation.

It is impossible to give a detailed example of all the conceivable variants. A limited number of variants have therefore been chosen from which the basic ideas of the design emerge.

First of all the "old" (deterministic) calculation of the Zeeburg tunnel is considered, whereby the results of the calculation are compared with the measurements. The differences between the measurements and the calculations are accounted for.

After which the ventilation design for the Zeeburg tunnel is calculated according to the "new" (probabilistic) calculation method with the new starting points and the differences are accounted for.

Finally, the effects of the following parameters will be studied by using the new calculation method:

- tunnel length: a longer length of 1,000 and 2,000 m instead of 530 m
- the number of traffic lanes: 2 instead of 3 traffic lanes
- gradient: a flat tunnel 2,000 m long instead of a tunnel with gradients
- the distribution of the number of boosters
- orientation of the tunnel axis
- the surroundings of the tunnel openings: a "town" tunnel instead of a tunnel situated in an unrestricted area.

11.2 CALCULATION ACCORDING TO THE DETERMINISTIC METHOD

Project data

The Zeeburg tunnel is situated in the eastern section of the A10 ring road round Amsterdam and has been in use since September 1990. The tunnel axis is almost north-south, in which the two tunnel openings are somewhat twisted in relation to each other due to a horizontal bend with a radius of 1000 m. Since the difference in the angle

(approx.10°) is small, it is not taken into account. The surroundings can be classified as an outside area. The shape of the tunnel openings is "classic": exits with high concrete walls and a sun-reflecting grid system in both entrance openings. The exit openings do not have a sun-reflecting grid system.

Longitudinal profile

The total length of the enclosed part of the tunnel is 530 m consisting of the following sections:

- 200 m with a gradient of -4.5%
- 130 m is horizontal, gradient 0.0%
- 200 m with a gradient of +4.5%

Cross section

The tunnel has two separate tunnel tubes for oneway traffic. Two-way traffic is only permitted in exceptional circumstances.

The road way has 3 traffic lanes with a maintenance lane and a so-called New Jersey profile on both sides. This brings the width of the tunnel to 13.0 m. The permissible height for traffic is 4.0 m. It is stipulated at an international level that viaducts and other engineering works in international routes must be a minimum of 4.5 m high. Since a minimum of 0.40 m is required for lighting and traffic lane signposting, the height of the tunnel tube comes to 4.90 m. The cross section is uniform along the whole length of the tunnel.

The surface area of the cross section is 13.0 x 4.90 = 63.7 m^2 . There is a chamfer in both top corners of the tunnel tube which has been made for structural reasons concerning concrete. In addition the NJ profile takes up some space resulting in a final cross-sectional area of 60 m^2 with a circumference of approx. 35.8 m.

Other data

The transport of dangerous substances is permitted (category 1).

A minimum air speed of 5 m/s is required in the event of a "large" fire; and 3 m/s for a "medium-sized" fire.

The available space for boosters is very limited with respect to the clearance space profile. The ideal position for the boosters would be on the ceiling and installed next to each other. As a result of the available height the boosters have to be moved to the top corners. Due to the transverse slope of the road surface, most space for the boosters in the eastern tunnel tube is available on the outer wall and in the western tunnel tube on the inner wall. This position is very bad for the eastern tunnel tube due to the horizontal curvature. Checking measurements taken in the tunnel have indicated this phenomenon.

11.3 STARTING POINTS FOR THE DETER-MINISTIC CALCULATION

The calculations were made with the "old" computer program which was used at Directorate-General for Public Works and Water Management known as the "v1.2 program".

11.3.1 Scenario

4 different operating situations (scenarios) were distinguished, namely: stagnating traffic, emergency assistance, escaping motorist and fire. The starting points adopted for each scenario are given below.

Stagnating traffic

It is assumed that the traffic moves through the tunnel with a tailback. The tailback is of the closed type, therefore there are no gaps between the vehicles, the speed of which is more than 2 km/h.

The number of vehicles and the time spent in the tunnel can be worked out on the basis of this speed.

The design wind speed is 15 m/s in an unrestricted air space at a height of 10 m.

Emergency assistance

To give emergency assistance in the event of small accidents and traffic jams, the emergency service personnel work in the tunnel tube for a maximum of 1 hour. If more time is required to solve the problems, the whole tunnel tube is blocked off to enable assistance to be given safely.

The traffic in the other traffic lanes, can leave the tunnel, travelling in a file at an average speed of 2 km/h. There are therefore 2 traffic lanes in use with an average speed of 2 km/h.

The design wind speed is 15 km/s in the unrestricted air space at a height of 10 km.

Escaping motorist

The following starting points were used:

- site of the accident: near the tunnel exit opening
- waiting time: 10 min., activity "sitting"

- thereafter walking out of the tunnel in the direction of the tunnel entrance, activity "working"
- half of the stranded motorists will not turn off the engines
- all the traffic lanes are occupied by traffic
- the design wind speed is 10 m/s in the unrestricted air space at a height of 10 m.

Fire

No scenario for fire was included in the recommendations made in 1975. At that time not enough attention had been paid to the phenomenon fire. At the end of the 1970s and the beginning of the 1980s this changed because of the fire in the Velser tunnel in 1978. In addition, due to developments in the field of the transport of dangerous substances, extra attention was given to the danger of a tunnel fire.

The original computer program was not provided with a calculation for fire. To nevertheless be able to take fire into account the program was adapted as far as possible at the time. This adaptation was, however, fairly simple due to the limited possibilities of the original computer program. The results of these calculations are not very accurate and are difficult to compare with the results of the probabilistic method.

The following starting points were initially taken into account. There were three possible scenarios, namely a "small", a medium-sized" and a "large" fire. A short description is given below of what was understood at the time to be meant by these three types of fire:

- A "small" fire is a fire in which a car is completely burnt out. This type of fire is not normative therefore further calculations were not made.
- A "medium-sized" fire is a fire in which a goods vehicle laden with wood is completely burnt. This type of fire is probably also not normative. A checking calculation was, however, made.

The heat production for the goods vehicle was taken to be 100 MW. The temperature of the fumes will reach about 800° C.

The ventilation speed required to drive the fumes to one end of the tunnel is 3 m/s.

The design wind speed is 10 m/s in the unrestricted air space at a height of 10 m.

- A "large" fire is a fire in which a tanker laden

with 50 m³ of petrol is completely burnt. The heat production is taken to be 300 MW. The temperature of the fumes is very high, more than 1400° C. As a result of which the damage to the tunnel interior is very great downstream from the fire.

The ventilation speed required to drive the fumes to one end of the tunnel is 5 m/s.

The design wind speed is 10 m/s in the unrestricted air space at a height of 10 m.

11.3.2 Breakdown of ventilators

The program used in the past did not allow for the possible breakdown of ventilators in the calculation. At least several boosters will break down as a result of the high temperatures which arise. If this fact is to be taken into account, then a manual correction must be made to the "v1.2 program".

11.3.3 Danger of explosion

The danger of explosion was not taken into account in the calculation made according to the "old" (deterministic) method.

11.3.4 Direction of ventilation during a fire

The old starting points were:

- it was decided to drive the combustion gases to one end of the tunnel to make fire fighting possible and to limit damage as much as possible. The normal direction of ventilation is always in the same direction as the traffic towards the exit opening.
- an air speed in the tunnel tube of 3 m/s is exactly enough for the "medium-sized" fire but a minimum speed of 5 m/s is required in a "large" fire to drive all the products of combustion to one end of the tunnel.

11.3.5 Site of the fire

The old starting points were:

- the site of the fire is connected to the site of the accident. In practice it appears that most accidents and therefore most fires occur in the second half of the tunnel
- for reasons of simplicity it was proposed that the fire breaks out near the exit opening and the whole tunnel tube is filled with traffic.
- 11.3.6 Other parameters relevant to the calculation
- The ventilation system must be reversible.

- An allowance of 20% is made to take the production of smoke by diesel traffic into account.
- The composition of the traffic is as follows: 10% goods vehicles and 90% cars.
- The roughness of the surrounding area is taken into account by employing a reduction factor of 0.7 for the wind.
- The wind pressure coefficients at the tunnel entrance and exit openings are taken to be +0.7and -0.55, respectively. These values must be added together as absolute values to give a shape factor of 1.25.
- The overall efficiency of the boosters is taken to be 75%. This value is considered attainable because deflection blades are fitted. Efficiency falls to 60 to 65% without deflection blades.
- In the "stagnating traffic" and "escaping motorist" scenarios a maximum permitted value of 300 ppm applies to the CO concentration. A maximum CO concentration of 150 ppm applies to "emergency assistance". No requirements have been made for the "fire" scenario.
- Two-way traffic is not possible in the normal operating situation in the tunnel tube. Two-way traffic is only permitted in the event of disasters and during maintenance work.
- The permitted concentration of smoke (normative for deterioration in visibility) is in the case of:

•	stagnating traffic	k	=	0.004	m-1
	emergency assistance	k	=	0.002	m^{-1}

 Novenco ventilators were chosen, type AFR-728/280, speed of revolutions 2950 rpm, voltage 3x380 V, 50 Hz. Temperature resistance is 250°C for a maximum of 1 hour. The boosters have been fitted with deflection blades.

To determine the number of ventilators the following specifications are taken into account:

-	motor power	: 18.5 KW
-	power consumption	: 19.4 kW
-	ventilator output rate	: 12.5 m ³ /s
-	outlet rate	: 40.5 m/s
-	nominal impulse	: 607 N
-	measured impulse	: 580 N
_	specific impulse	: 29.9 N/kW

1.4 CALCULATIONS TO BE MADE

The calculation aims to determine the number of ventilators required for the different scenarios.

11.4.1 Summary of calculation results according to the "old" method

Table 11.1 gives a summary of the required number of ventilators calculated by the "v1.2 program" of the Engineering Division of Directorate-General for Public Works and Water Management.

TABLE 11.1

Number of ventilators according to "old" method

scenario	CO ca CO con tion	lculation ncentra-	smoke o deterio in vis:	fire	
	150 ppm	300 ppm	0,002	0,004	
stagnating traffic	-	15,3	-	13,9	
emergency assistance	16,2	-	14,0	-	
escaping motorist	-	8,1	-	6,2	
brand ut≖ 3 m/s					11,8
fire ut= 5 m/s					27,9

11.4.2 Choice of the number of ventilators

The number of ventilators installed in the Zeeburg tunnel is 15. According to Table 11.1 28 ventilators are required. Yet it was decided to fit 15 ventilators for reasons which will not be considered here.

The installed capacity therefore comes to 15×18.5 = 277.5 kW. The power consumption according to laboratory measurements is 291 kW.

11.4.3 Checking measurements taken in the tunnel

The power consumption is smaller than the abovementioned 291 kW due to the flowing tunnel air ("on-stream" effect). The electric current consumed has not been systematically measured in relation to the prevailing ventilation speed in the tunnel tube. Several measurements and at an air speed of approximately 7 m/s indicate that the electric current consumed amounts to 28 A. The nominal electric current is 31 A in the case of stationary surrounding air.

Measurements of the average ventilation speed taken

when there was no wind and no traffic with all the boosters operating are given in Table 11.2.

TABLE 11.2:

Results of checking measurements of the ventilation speed in the Zeeburg tunnel

	air speed in m/s				
tunnel tube	normal venti- lation direc- tion	opposite venti- lation direc- tion			
western tube	7,03	7,9			
eastern tube	5,7	7,1			

It is not possible to make a calculation for an empty tunnel tube with the "old" calculation program. This can, however, be made manually in a simple way.

Total efficiency

At an average air speed of 7.00 m/s the dynamic energy in the air is:

$$P_{air} = \frac{1.2xA_txu_t^3}{2000} = 12.35 \text{ kW}$$

The total power consumption from the mains at an average $u_t = 7$ m/s is:

$$P_{net} = 15 \times 19.4 \times \frac{28}{31} = 262.83 \text{ kW};$$

or 17.52 kW per booster.

The total efficiency is therefore:

$$\eta_{\text{tot}} = \frac{P_{\text{air}}}{P_{\text{mains}}} x 100\% = \frac{12.35}{262.83} x 100 = 4.7\%$$

Inventarisation of the losses

In view of the large difference between the power transferred to the ventilation air and the power consumed from the mains it is interesting to find out where the losses occur. Several measurements have been taken in the Zeeburg tunnel to locate the most important losses. The losses were caused by:

- the inflow and outflow losses
- the wall friction
- the loss in the boosters
- the loss incurred to overcome the difference in wind pressure

the positional loss.

The extent of the various losses was worked out for the western tunnel tube.

Inflow and outflow losses

Measurements have shown that the inflow coefficient is 2.2 and the outflow coefficient is 0.3. The difference between the inflow coefficient for the eastern and western tunnel tubes is marked, namely 2.7 and 2.2, respectively. The explanation for this must be sought in the sun-reflecting grid structure. The slats in this structure on the inflow side of the eastern tunnel tube have a particularly bad aerodynamic shape. Taking the numerical values for the western tunnel tube into account the sum of the inflow and outflow coefficients is 2.5. This produces a loss of:

$$R_{in/out} = 2.5 x \frac{1}{2} x 1.2 x u_t^2 x A_t = 4410 N$$

This gives a required power of:

$$P_{in/out} = \frac{Q_{txR_{in/out}}}{1000 \text{ x A}_{i}} = \frac{7.0 \text{ x } 60 \text{ x } 4410}{1000 \text{ x } 60} = 30.87 \text{ kW}$$

Wall friction

Wall friction depends on the wall friction coefficient λ_w . The value of this coefficient is difficult to determine but can contribute to considerable losses. If $\lambda_w = 0.016$ then:

$$R_{empty} = \lambda_{w} x \frac{L}{D_{h}} x \frac{1}{2} x \rho x u_{l}^{2} x A_{l}$$

it follows from this that:

With
$$D_h = \frac{4 \times A_t}{O_t}$$

If $\lambda_w = 0.025$ then R_{empty} is calculated to be 3489 N.

Expressed in terms of the power required if $\lambda_w = 0.016$, then:

$$P_{wall} = Q_t \times \frac{R_{empty}}{1000 \times A_t} = \frac{7.0 \times 60 \times 2233}{1000 \times 60} = 15.63 \text{ kW}$$

If $\lambda_w = 0.025$, $P_{wall} = 24.42$ kW.

Loss in the boosters

The loss can be calculated from the capacity measurement taken in the laboratory. In the case of stationary surrounding air the loss per booster amounts to:

$$P_a = P_{mains} - P_{air} = 19.4 - \frac{Q_a x \frac{1}{2} x \rho x u_a^2}{1000}$$

$$= 19,4 - 12,3 = 7,1 \text{ kW}$$

The situation in the tunnel deviates from the conditions in the laboratory. Due to the operation of the boosters an equilibrium is reached between the losses and the energy transferred to the air. The air speed increases until an equilibrium is reached, for the losses increase with the air speed. A booster installed in the tunnel will be not be able to transfer any more energy to the tunnel air than that permitted by the ambient air speed. Or in other words the transfer of energy to the surrounding air depends on the speed of this air. In the case of flowing surrounding air, such as occurred during the measurement in the tunnel, the loss per booster is:

$$P_a = P_{mains} - P_{air} = 17.52 - \frac{Q_a x^{1/2} \times \rho \times (u_a - u_i)^2}{1000}$$

Since the output from the booster increases a little as a result of the "on-stream" effect a correction has to be made for this. This effect is measured in the laboratory. It is reasonable to assume that Q_a in the tunnel increases at a speed of 7.0 m/s from 12.5 to 13 m³/s. Substitution of these values in the equation gives:

$$P_{air} = \frac{13 \times 0.5 \times 1.2 \times (40.5 \times 13/12.5 - 7)^2}{1000} = 9.62 \text{ kW}$$

 $P_a = 17,52 - 9,62 = 7,9 \text{ kW}$

The total loss in the boosters amounts therefore to $15 \times 7.9 = 118.5 \text{ kW}.$

Loss due to the pressure difference between the two openings

To be able to displace the tunnel air the difference in wind pressure between the entrance and exit openings must be overcome by the ventilation system. The energy which is involved in this is:

$$P_{\Delta p} = \frac{Q_t x \Delta p}{1000}$$

The static pressure difference Δp was not measured during the measurements. The pressure difference can be estimated based on a calculation. If $\Delta p = 20$ Pa, then the power required is:

$$P_{\Delta p} = \frac{7.0 \text{ x } 60 \text{ x } 20}{1000} = 8.4 \text{ kW}$$

Positional losses

Positional loss is understood to mean the loss which occurs as a result of the friction operating on the air blown out which flows at high speed along the tunnel walls, ceiling and surface of the road. The speed of the outlet air is very high especially in the first few metres after the boosters. In the Zeeburg tunnel this loss has been tried to be made as small as possible by the use of deflection blades. The extent of these losses has not been able to be measured up to now.

Energy balance

If the energy balance is considered then this appears to be built up as follows for variant 1 ($\lambda_w = 0.016$) and variant 2 ($\lambda_w = 0.025$):

	variant1	variant 2
- dynamic energy in the air	12.35 kW	12.35 kW
- inflow and outflow losses	30.87	30.87
- wall friction	15.63	24.42
- loss in the boosters	118.50	118.50
- wind pressure difference	8.40	8.40
- balance positional loss	77.08	68.29
- supplied from mains	262.83 kW	262.83 kW

A positional loss of 77.08 kW and 68.35 kW, respectively must be accounted for to make the total amount of energy balance. The positional efficiency is then calculated to be:

 $\eta_{o \text{ variant } 1}$:

$$\frac{262.83 - 77.08}{262.83} \times 100\% = 70.67\%$$

 $\eta_{o \text{ variant } 2}$:

$$\frac{262.83 - 68.29}{262.83} \times 100\% = 74.02\%$$

Conclusion

It is not easy to determine the separate losses. An extensive programme of measurement must be carried out under favourable weather conditions. The above-mentioned exercise, which was carried out for the Zeeburg tunnel, illustrates this point. The results only apply to the Zeeburg tunnel and are not representative of other tunnels.

11.5 ZEEBURG TUNNEL CALCULATED AC-CORDING TO THE PROBABILISTIC METHOD

First of all the most recent starting points must be specified for the Zeeburg tunnel. These starting points are given in Chapter 2 and are summarized here.

Stagnating traffic

The traffic moves forward in 95% of cases at a speed of more than 6 km/h. There are no gaps between the vehicles in the traffic jam so that the maximum density of the traffic occurs. The permissible deterioration in visibility k_t is 0.004 m⁻¹.

Emergency assistance

The emergency service workers give assistance for a maximum of 1 hour. One traffic lane is blocked off to help the emergency service workers, the traffic in the other lane travels at a speed of 25 km/h. The permissible deterioration in visibility is half of the value for stagnating traffic.

Escaping motorist

There a total long-lasting obstruction of the tunnel due to an accident. As a result of which the public must leave the tunnel on foot. All the traffic lanes are completely occupied by vehicles.

Fire

In the event of a "small" fire all the ventilators remain in operation, therefore also upstream from the

fire.

In the event of a "medium-sized" fire the extent to which the high temperature is the cause of the breakdown of the boosters must be shown from a separate calculation.

In the event of a "large" fire all the boosters within a distance of 300 to 500 m downstream from the fire break down. In this situation the site of the fire is of great importance because it determines the remaining ventilation capacity.

The normative fire is the "large" fire because it results in the breakdown of the largest number of ventilators which are no longer able to contribute to the ventilation capacity.

To reduce the probability of the ventilators breaking down installation of the ventilators in the tunnel entrance opening is the best solution. The program gives the possibility of making a separate input for ventilators distributed over the length of the tunnel and for ventilators in the entrance opening.

Danger of explosion

A minimum volume of air is required for the "large-"fire to guarantee complete combustion and to reduce the possible risk of an explosion. This volume of air is 88 m³/s. With a cross sectional area of 60 m^2 the speed works out to be 1.47 m/s.For the "medium-sized" and the "small" fire the volumes of combustion air are much smaller, therefore no more attention is given to this aspect.

A separate calculation can be made for both tunnel tubes with the "new" (probabilistic) method. The effect of the prevailing wind direction emerges from this calculation.

A calculation is made for each tunnel tube by taking the coefficients as used in the "old" (deterministic) method (see columns 2 and 5 of Table 11.3). After which a calculation is made in which the coefficients actually measured in the tunnel (see columns 3 and 6 of Table 11.3) are taken into account. Finally an optimization calculation is made taking into account the latest ideas with several boosters in the entrance opening and several distributed over the length of the tunnel (see columns 4 and 7).

11.5.1 Calculation results of Zeeburg tunnel according to the "new" method

Table 11.3 gives an overview of the required number of ventilators according to the "old" (deterministic) and the "new" (probabilistic) methods.

TABLE 11.3:

Number of ventilators according to the "old" and "new" methods

	old pro- gram								
	v1.2	wester	n tunnel tube		eastern tunnel tube				
Ť	starting points according to old calculation	starting points according to old calculation	starting points according to results measure- ments	optimi– zation	starting points according to old calculation	starting points according to results measure- ments	optimi– zation		
column	1	2	3	4	5	6	7		
stagnating traffic	15,3	_	< 5	-	_	< 3	_		
emergency assistance	16,2	_	-	-	-	-	-		
escaping motorist	8,1	-	-	_	-	-	-		
fire 3 m/s	11,8	_		-		_	-		
fire 5 m/s	27,9	_		_		-	-		
fire 88 m ³ /s	_	12	13	4–5	10	13	4-4		

Explanation of Table 11.3

The calculations show that the "fire" scenario produces the normative values. For this reason this calculation has principally been included in this chapter. A checking calculation has, however, also been given for the "stagnating traffic" scenario. It appears that the number of ventilators for this situation is particularly small. A check has not been carried out on the other scenarios because it appears from checking calculations made on other tunnels that these scenarios are not normative.

Separate calculations can be made on both traffic tubes by using the new method because the data on the position of the openings can be inputted separately. It appears that in the eastern tunnel tube a somewhat smaller number of ventilators can be sufficient compared to the western tunnel tube, which is also to be expected because of the prevailing wind direction. The difference is, however, marginal and amounts to a maximum of 2 ventilators. The calculation which uses coefficients measured in the tunnel shows in the event of fire(88 m^3/s) that the number of ventilators is the same because the inflow coefficient is worse for the eastern tunnel thus counteracting the favourable effect of the orientation.

The results, based on the starting points of the old calculation, for the eastern and western tunnel tube are given in appendices E1 and E2, respectively.

It can be deduced from Appendix E1 that the probability of going below the required values of 88 m^3/s is 0.003 or in other words this minimum volume is not met in 1 out of 333 "large" fires. The standard is 1 in 200 "large" fires therefore the eastern tunnel adheres to the standard. The required number of ventilators is 10.

It can be deduced from Appendix E2 that the probability of going below the 88 m^3/s is also 0.003. For the probability of going below the standard value to be the same for both tunnel tubes, 12 ventilators must be installed in the western tunnel tube.

11.5.2 Accounting for the differences between the old and new calculations

The air speeds of 3 and 5 m/s which were also the required air speeds in the past are given in Appendix E2. This graph shows that for 12 boosters the speed of 5 m/s is not realized in all cases and that in about 1 in 12 fire situations the speed of 3 m/s is not attained. If the same probability of going below the standard value is given to these air speeds as is given to 88 m³/s, then the number of ventilators must be considerably higher. Appendix E3 shows that in the case of 40 ventilators the required air speed and the associated probability of 0.005 of falling below the standard value are satisfied at 3 m/s as well as 5 m/s. This number is comparable to 27.9, the number calculated according to the old method. The difference in number arises because the old program did not take the breakdown of the ventilators into account whereas the new program does.

If the number of ventilators is reduced to 30, then only the speed of 3 m/s still satisfies the probability of falling below the standard value (see Appendix E4).

The extent to which it is reasonable to demand these air speeds will become apparent in the future. Until then the minimum requirement of 88 m^3/s will be taken as the basis. After the results of the fire tests, made in America in 1991, have been published, information will become available so that these values can be adjusted.

The small number of boosters in the "stagnating traffic" scenario can be explained by the lower traffic density compared to 1975 and the reduced emission from the total number of vehicles. The numbers emerging from the test calculations for the "emerge-ncy assistance" and "escaping motorist" scenarios are also smaller than calculated according to the old method.

The lower number of boosters for the "fire" scenario can be explained by the much smaller volume of air which has currently been set as the minimum requirement.

11.5.3 Conclusions

The number of boosters installed in the Zeeburg tunnel amounting to 15 distributed over the length of the tunnel satisfies the most recent ideas concerning the fire-proof ventilation of road tunnels which have been opened to the transport of dangerous substances.

The calculations show in addition that a saving in the number of ventilators is possible in future ventilation systems. The combined system, in particular, offers extremely interesting possibilities. A saving of 30 to 40% on the number of ventilators in tunnels similar to the Zeeburg tunnel is one of the possibilities. It will become evident further on in the text that the advantage of the combined system comes out especially in the favour of shorter tunnels.

11.6 RESEARCH ON THE EFFECT OF THE DIFFERENT PARAMETERS

11.6.1 Starting points

The starting points made in the checking calculations for the research on the different parameters are:

- orientation of tunnel east-west
- northern tunnel tube
- wall friction coefficient 0.025
- positional efficiency 60%
- inflow coefficient 2.2
- outflow coefficient 0.3
- percentage of goods vehicles 10%
- gradient 4.5%, horizontal, + 4.5%

The results of about 100 checking calculations are summarized in Table 11.4. For comparison this table also gives the number of ventilators calculated according to the old program, in which the same starting points are used as much as possible. Only a few checking calculations have been carried out for the situations which are not normative because the required calculation time for the probabilistic calculations would otherwise take up too much time.

TABLE 11.4:

	old method			new method						
scenario	ario tunnel length+(m)		tunnel length (m)							
	530	1000	2000		530		1000		2000	
				at front	distributed	at front	distributed	at front	distributed	
Two-lane tu	innel tu	ibe *):								
fire	23	34	35	0 5 8	38 28 22	0 5 8	24 17 13	0 5 8	25 19 15	
stagnating traffic	20	25	240	_	_	_		_	_	
emergency assistance	20	23	49		-	-	-	-	_	
escaping motorist	10	17	158	_	_	_	_	-	-	
Three-lane	tunnel	tube *):								
fire	31	45	76	0 5 8	35 25 20	0 5 8	24 17 14	0 5 8	25 19 15	
stagna– ting traffic	25	36	570	_	_	_	_	_	_	
emergency assistance	26	40	171	_	-		_	0 10	90	
escaping motorist	13	29	376	-	_	-	_	_	_	

Number of ventilators according to the "old" and "new" methods

*) starting points:

positional efficiency
wall friction coefficient

: 0.025

: 60%

: 2.2

- inflow coefficient

- outflow coefficient

: 0.3 : 10%

percentage goods vehiclesgradient of tunnel

: -4.5, 0 and +4.5%
11.6.2 Effect of tunnel length

The Zeeburg tunnel, which is 530 m long, is taken as the reference. Tunnels which are 1000 or 2000 m long are compared to this reference length.

The old method shows a very progressive development in the number of ventilators with increasing length. This is particularly noticeable in the "stagnating traffic" and "escaping motorist" scenarios (see Table 11.4).

The new method produces a larger number of ventilators at shorter tunnel lengths. The tunnel length of between 1000 and 2000 m has hardly any effect on the number of ventilators in the "large" fire scenario. To what extent this trend is continued for tunnel lengths longer than 2000 m has not been verified. It is expected that the increase in number is very limited for this scenario.

The other scenarios do not give any normative numbers of ventilators, except for the "emergency assistance" scenario in a three-lane tunnel 2000 m long, which produces a very large number of ventilators. This is not the case for 1000 m, so that a tunnel length can be found between 1000 and 2000 m at which "emergency assistance" is normative. These calculations have not been made but can be made in the future if there is reason to do so.

If the results of the old method are compared with those of the new method for the "fire" scenario, it is evident that the difference in the number of boosters is not very great in short tunnels but the number of ventilators calculated by the old method is clearly higher in longer tunnels. The explanation for this is as follows:

- Shorter tunnel length

The old program did not take the breakdown of the ventilators into account, which results in the number of ventilators being too low. The required air speed of 5 m/s, however, produces a larger number of ventilators. The new basic assumption, the minimum air volume of

 88 m^3 /s gives a lower number. If the number of ventilators is worked out by using the new program with the old requirement of 5 m/s, then 40 ventilators are required (see Appendix E3).

– Longer tunnel length

The calculation for the longer tunnels by using the old program and at the required air speed of 5 m/s results in a considerable wall friction resistance. The new method is based on a much

lower ventilation speed because the required output flow rate has been decreased to $88 \text{ m}^3/\text{s}$. If the new program calculates on the basis of an air speed of 5 m/s, then this will also result in a considerable resistance and accordingly in a large number of ventilators. The number of ventilators required in a three-lane tunnel tube are given in Appendix E5 to give an impression of the numbers involved at a speed of 5 m/s. In a tunnel 2000 m long about 100 ventilators are required. Compared to the results of the old program of 76 ventilators, this is an increase in the number. This is due to the fact that value can only be attached to the old number, if the wind speed is also 10 m/s on which the calculation has been based. This is of overriding importance. If the wind speed increases to 15 m/s then the old program calculates 90 ventilators. If a lower speed is adopted, for example 5 m/s, then the number of ventilators is 68.

11.6.3 Effect of the number of traffic lanes

In the "large" fire scenario the number of traffic lanes has hardly any effect on the number of ventilators in tunnels between 1000 and 2000 m long. The number of lanes has some effect in tunnels 530 m long because a comparatively larger percentage of the breakdown of ventilators is taken into account.

The most important effect of the number of traffic lanes is to be seen in the "emergency assistance" scenario. In this scenario the number of boosters is normative for a three-lane tunnel tube which is 2000 m long.

In 2-lane tunnels this scenario is normative in tunnels longer than

2000 m. The checking calculation has not been made so that it is not known at what tunnel length this is the case.

The old method shows a clear effect of the number of traffic lanes.

In the calculated example given in 10.6 a factor of 1.2 is given for the difference in the number of traffic lanes. This factor only applies to the example used. The calculations presented here show that the number of traffic lanes has hardly any effect. It is presumed that the substituted coefficients are the cause of this.

11.6.4 Effect of gradients

The effect of gradients is given in Table 11.5 for the "fire" scenario and in Table 11.6 for the "stagnating traffic" scenario.

TABLE 11.5:

Effect of gradients in the "fire" scenario

	2-lane tunn	el-tube	3-lane tunne	el tube
	probability of going below (-)*	number venti- lators (-)	probability of going below (-)*	number venti- lators (-)
-horizontal 2000 m	0,028	15	0,035	15
-gradient 800 m -horizontal 400 m -gradient 800 m	0,028	15	0,035	15

* probability of going below 88 m³/s

TABLE 11.6:

Effect of gradients in the "stagnating traffic" scenario

	3-lane tunnel tube					
	probability of going below (-)*	НЬ-СО (%)	number venti- lators (-)			
-horizontal 2000 m	0,025	2	25			
-gradient 800 m -horizontal 400 m -gradient 800 m	0,025	2	25			

* probability of going below 88 m^3/s .

Conclusions from Tables 11.5 and 11.6:

- no effect can be seen of the gradient percentage in the "stagnating traffic" scenario
- detailed calculations have shown that a reliable effect of the gradient percentage is found but that this effect is so small that it cannot be seen in a graph. The effect is therefore marginal and can be disregarded
- there is no effect of the gradient in the "fire" scenario because the traffic is stationary.

11.6.5 Effect of the distribution of the boosters over the length of the tunnel

It is not possible to make a distinction between the number of boosters in the entrance opening and those distributed over the tunnel length by using the old program. But this is possible in the new program. In making the distinction it was investigated where the reduction in the number of ventilators could take place. The effect of the distribution is shown in Table 11.4 and produces information for Table 11.7.

TABLE 11.7:

Effect of the distribution of the boosters.

		tunnel length							
number venti- lators	9	530 r	B		1000	B	20	000 r	D
in tunn e l opening	0	5	8	0	5	8	0	5	8
distributed over length of tunnel	38	28	22	24	17	13	25	19	15
total	38	33	30	24	22	21	25	24	23
difference		5	8		2	3		1	2

Conclusion from Table 11.7:

A clear saving in the number of ventilators is possible for the usual tunnel lengths of 500 to 800 m. This advantage decreases, however, as the length increases.

11.6.6 Effect of the orientation of the tunnel axis The effect of the orientation of the tunnel is given in Table 11.8.

TABLE 11.8:

Probability of going below the standard value in the "fire" scenario.

	tunnel length							
	530 r	0	2000 m					
orientation tunnel axis	probability of going below stan- dard (-)*	number venti- lators (-)	probability of going below stan- dard (-)	number venti- lators (-)				
north east south west NE-SW	0,012 0,002 0,0012 0,004 -	15 15 15 15 -	0,035 0,007 0,005 0,010 0,040	15 15 15 15 15				

* probability of going below 88 m³/s

Conclusions from Table 11.8:

The effect of the position of the tunnel openings with respect to the points on the compass is clearly discernable. The worst orientation of the tunnel tube is northeast-southwest, in which the normal direction of the traffic is towards the southwest. The effect as given above depends on the geometry of the tunnel and has been outlined in the calculation model as indicated in Appendix D. The results for tunnels with different geometries will be different.

11.6.7 Effect of the immediate surroundings of the tunnel openings

The effect of the surroundings can be divided into a correction for the effects of the surroundings and a correction for the altitude. If wind tunnel measurements are available of the tunnel openings and the immediate surroundings, the correction for the surroundings and the altitude can be left out. The only correction which should be made is the correction for the difference in wind speed at the meteorological station and the wind speed at a height of 10 m.

The effect of the surroundings can be inputted by means of the surroundings factor (f_o) , with which the reduction in the effect of wind due to buildings but also of the tunnel structure itself can be allowed for. See Table 11.9 for the effect of this factor.

If no model research calculations are available, then the height correction factor (f_h) can be used with which the altitude of the tunnel opening can be allowed for. See Table 11.10 for the effect of this factor.

Tables 11.9 and 11.10 do not give *any* normative values but are only included to illustrate the effect of these factors on the calculation.

The standard measurements taken by the KNMI are published for the "open" field at a height of 10 metres above ground level. Since the tunnel openings usually lie below ground level a reduction can be applied to the KNMI values.

Both corrections can be entered in great detail into the program thus making an accurate calculation of the wind effect possible.

TABLE 11.9:

effect of the surroundings factor

orien- tation of tunnel axis	number of venti- lators	tunnel length (m)	f surroun- dings (-)	probability of falling below 88 m3/s
east	15	530	0,5	0,0004
east	15	530	0,7	0,0006
east	15	530	1,0	0,01

Conclusions from Table 11.9:

The effect of the reduction factor of the surroundings is very progressive. It is therefore important to give attention to the specification of this factor.

An increase in the number of ventilators by a factor of 3 to 4 is the result of a difference in the surroundings factor of 0.5 or 1.0.

The effect of the altitude of the tunnel openings is given in Table 11.10.

TABLE 11.10:

Effect of the altitude of the tunnel openings'

cal– cula– tion no.	orientation of tunnel axis	no. vent. (-)	tunnel length (m)			difference bet- ween the vari- ants of f_h in the probability of going below the value (-)	difference bet- ween the vari- ants of no. of ventilators in the probability of going below the value
column	1	2	3	4	5	6	7
1 2	west west	10 10	530 530	0,065	0,025	0,040	
3 4	west west	20 20	530 530	0,01	0,001	0,009	} 0,031
5	east east	15 15	530 530	0,020	0,002	0,018	}
7 8	east east	20 20	530 530	0,006	0,0005	0,0055	J 0,0125
9 10	north north	15 15	530 530	0,050	0,015	0,035	} 0,01
11 12	north north	20 20	530 530	0,03	0,005	0,025]

: 60%

: 0.025

: -4.5, 0

4.5%

+

- positional efficiency

- wall friction coefficient
- inflow coefficient
- : 2.2 - outflow coefficient : 0.3
- percentage goods vehicles : 10%
- gradient of tunnel
- and

Conclusions from Table 11.10:

A larger height correction factor (f_b) requires a larger number of ventilators as can be seen in columns 4 and 5.

The effect of the orientation of the tunnel openings can be seen by comparing calculation numbers 3/4, 7/8 and 11/12. The difference between the probabilities of going below the standard value for the various orientations indicates that with the same number of ventilators the northward tunnel tube has the highest probability of going below the value, followed by the westward and eastward tunnel tube.

Therefore there is a clear indication of a directional dependency of the height correction factor (see column 6).

There also seems to be a dependency of the number of ventilators (see column 7).

11.7 GENERAL COMMENTS ABOUT THE EFFECT OF WIND

If wind speeds in m/s are compared with the Beaufort scale, then 20 m/s is equivalent to wind force 8, while 15 m/s is equivalent to wind force 7 and 10 m/s represents wind force 5 to 6 on this scale. A table comparing the wind speeds and their descriptions, which are accepted in meteorology, is given below in which the wind speeds have been rounded to the nearest half metre per second.

TABLE 11.11

Comparison of Beaufort scale and wind speeds in m/s

Beaufort scale	description	wind speed in m/s
1	light wind	< 1.5
3	moderate wind	3.5 - 5.5
5	fairly strong wind	8.0 - 10.5
6	strong wind	10.5 - 14.0
7	hard wind	14.0 - 17.0
8	stormy wind	17.0 - 21.0
9	storm	21.0 - 24.5

11.8 ECONOMIC ASPECTS OF THE VEN-TILATION DESIGN FROM THE TECH-NICAL POINT OF VIEW OF INSTAL-LATION

Not only the costs of the ventilators determine the final price of the ventilation system. A few other important price-determining aspects are:

- the connection to the energy supplying company
- the main distributor
- the power of the emergency system to be installed
- the cable work and the cable duct system
- the control system
- the installation costs
- the future maintenance costs.

All these aspects must be included in the determination of the number of ventilators. It is not possible to make a recommendation about the choice of the number of ventilators without the abovementioned information.

Broadly speaking it can be assumed that a smaller number of ventilators results in a better cost price of the ventilation system in spite of the higher price per impulse force unit supplied.

In particular, the costs of the main distributor, the emergency power supply and the installation costs are affected to a large extent by the choice of the number of ventilators.

The maintenance costs expected in the future are directly dependent on the number and the quality of the ventilators chosen. This aspect must be considered as well.

11.9 FINAL CONCLUSIONS AND RECOM-MENDATION

To enable an accurate calculation to be made it is recommended that model tests are carried out on both tunnel openings in order to check the assumption made about the shape and surroundings factors.

The Civil Engineering Division of Directorate– General for Public Works and Water Management will carry out model tests in the course of 1991 on tunnel openings with different geometries. As a result of this research better forecasts will be able to be made in the future of the effect of the wind on tunnel openings.

It is recommended that checking measurements are taken in the tunnel before opening any tunnel to be built in the future as a result of which the performance of the ventilation system can be unequivocally derived.

12 RELIABILITY MEASUREMENTS

(H. Speulman, L. Swart)

12.1 GENERAL

This chapter concentrates on the measurements which are necessary to be able to determine whether the requirements made have been met. By outlining the method of measurement a better comparison of the results of various tunnel projects can be made. The aerodynamic measurements taken in the laboratory as well as in the tunnel are considered. The acoustic measurement method is also established for the measurements in the laboratory as well as in the tunnel tube.

Another reason for giving extensive attention to this subject is the fact that up to now very little has been prescribed, as a result of which the technical specifications made by the manufacturers are not always comparable. By way of the information presented in this chapter we have tried to make it possible to include a reference in the construction specification or the agreement to relevant parts from this chapter. The guarantee measurements of the different booster manufacturers can then be compared with each other.

During the realization of a tunnel project inspections or measurements must be carried out to check if the delivered parts of the system comply with the data in the construction specifications and the specifications.

The above-mentioned measurements are called the reliability and checking measurements. The measurements described in this chapter mainly apply to longitudinal ventilation by means of impulse ventilators (boosters). The recommendations made for the boosters can also apply to longitudinal ventilation by means of an injector for the aerodynamic measurements in the tunnel tube.

To be able to compare the measurement results with the prescribed specifications the measurements must taken very accurately in an aerotechnical laboratory. The procedures to be followed are described in detail in this chapter.

12.2 LABORATORY MEASUREMENTS

The measurements in the laboratory must be carried out according to the current and applicable ISO standards or similar standards. In the laboratory the following data must be determined about the booster:

-	air volume fan-motor	(m³/h)
-	air volume motor-fan	(m³/h)
-	outflow air speed	(m/s)
-	driving force	(N)
-	efficiency	(%)
-	power consumed from the mains	(kW)
-	starting current	(A)
-	starting time	(s)
	sound energy	(dB)

The following measurements are described in sequence:

- air volume measurement
- driving force measurement
- operation of the deflection blades
- measuring the capacities and the efficiency
- measuring the sound energy of the booster.

12.2.1 Air volume

The air volume of a booster must be calculated on the basis of a pressure measurement taken in a testing room, as described in the following paragraphs. The calculation method is described in this paragraph and is based in principle on a pressure difference measurement over a calibrated measuring nozzle.

Description of the testing room

The testing room located in the same direction as the wind is composed as follows:

- test ventilator in inflow area
- air equalizer
- air volume measuring nozzle
- air equalizer
- sound absorber
- in series valve recorders
- booster fan with adjustable deflection blades, the motor is adjustable between 500 and 1400 rpm
- sound absorber
- air equalizer
- test ventilator in suction area (alternative).

The layout of the testing room is given schematically in Figure 12.1.



FIGURE 12.1:

Testing room

Pressure measuring rooms

The dimensions of the pressure measuring rooms (under/zero pressure) are $5.4 \times 5.4 \times 3.0$ m (h x w x d). The test ventilator is installed in the pressure room. The measuring room can be used for measurements of the outlet as well as the inlet side of the booster.

The measurement setup must be suitable to create a static pressure of between plus 200 and minus 200 Pa in the measuring room. The booster must be measured in the testing room at static pressures of + 150, 0 and - 150 Pa. The object of taking this measurement is to determine the QH curve in the range of the operation of the booster.

Air volume measuring nozzles

The air volume measuring nozzles are installed between the two pressure rooms of the testing room. The shape of the measuring nozzles is in accordance with Amca standard 210, with nominal diameters of 440 and 600 mm (see Figure 12.2). The nozzles are installed according to Figure 12.3. The exact diameters and bores used in the capacity calculations are also given on this diagram. The choice of the measuring nozzles to be used must be geared to the capacity of the booster to be tested.



FIGURE 12.2: Measuring nozzles



	Nozzle no.	<u>Diameter</u> (mm)	<u>Surface area</u> (m²)
,	1	600,2	0,28295
	2	439,7	0,15188
	3	599,7	0,28246
	4	440,0	0,15203
	5	599,6	0,28240
	6	439,8	0,15194
	7	599,7	0,28247
	8	440,0	0,15208
	9	599,6	0,28239

FIGURE 12.3:

Position of measuring nozzles

Manometers

The pressure differences were automatically measured and recorded during the tests by pressure transmitters. The average pressure differences were recorded electronically over an adjustable time interval of a minimum of 30 s.

Driving force and maximum capacities of the test ventilator

The test ventilator must be driven by an electric motor. This electric motor can be directly connected by a star delta connection of 3x380 Volts to a power output of 300 kW. The maximum decrease in current is 1500 A at 380 V.

Measurement of the power consumption

The power consumption from the power supply is recorded during the air volume measurements. The accuracy of this measurement should not deviate by more than $\pm 1\%$. For more information see 12.2.5 "Capacity and efficiency".

Definitions according to ISO/TC-117

The capacity of the test ventilator depends on the setup. ISO/TC-117 gives the following measurement setups:

- a. unrestricted suction and unrestricted outlet
- b. unrestricted suction and outlet with duct
- c. suction with duct and unrestricted outlet

d. duct suction and outlet with duct.

The test ventilator must be measured according to measurement setup a (see Figure 12.4). The suction losses of a ventilator with unrestricted suction and the outlet losses of a ventilator with an unrestricted outlet are considered to be internal ventilator losses.



 $p_v = p_{t2} - p_{t1} = p_{s2} + p_{d2} - p_b$



FIGUUR 12.4:

Test ventilator setup in measuring room

Calculation of the air volume by the measuring nozzles

The following variables are used in the calculation of the air flow rate in the test setup:

$$p_v = ventilator pressure$$
 (Pa)

- p_{t1} = total pressure in ventilator suction nozzle (Pa)
- p_{t2} = total pressure in ventilator outlet (Pa)
- p_{t1} = total pressure measured in the room before

		the ventilator					(Pa)
p ₁₂ '	=	total pressure	measured	in	the	room	after
		the ventilator					(Pa)

With the following indices:

- t = total pressure
- s = static pressure
- d = dynamic pressur
- 1 = ventilator nozzle
- 2 = ventilator outlet
- 1' = measuring room before ventilator
- 2' = measuring room after ventilator

The volume of air over the measuring nozzles (Q_n) is calculated from:

$$Q_{n} = \beta x \sqrt{\frac{2 x \Delta p_{n}}{\rho_{n}}} x \Sigma (C_{n} x A_{n})$$
(12.1)

where:

 $\beta = 0.122 \text{ x } \gamma^{1.42587} \text{ x } \frac{1 - \gamma^{0.2857}}{1 - \gamma}$ (12.2)

with:

$$\gamma = 1 - \frac{\Delta p_n}{\rho_n \ x \ 287.04 \ x \ (273.14 \ + \ t)}$$
(12.3)

where:

 Δp_n = pressure difference over the nozzles (Pa) ρ_n = density of the air in the nozzles (kg/m³)

t = temperature of the air before the measuring nozzles (°C)

$$C_n = 0.9986 - \frac{760}{\sqrt{Re}} + \frac{134.6}{Re}$$
 (12.4)

with:

Re = 70900 x D x $\sqrt{\Delta p_n}$ x ρ_n (12.5) where:

D	=	diameter	r of	the nozzl	le					(m)
D	=	0.44 m	for	nozzles	2,	4,	6,	8	(see	Fig.
		12.3)								(m)

$$D = 0.6 \text{ m}$$
 for nozzles 1, 3, 5, 7, 9 (see Fig. 12.3) (m)

 Δp_n = pressure difference over the nozzles (Pa)

The volume of air found here is the volume of air over the measuring nozzles.

Calculation of the volume of air at the test ventilator The volume of air in the suction nozzle of the test ventilator is calculated from:

$$Q_{a} = \frac{\rho_{n}}{\rho_{l}} \times Q_{n}$$
(12.6)

where:

0

Q,	=	air flow rate of the booster	(m^3/s)
ρ_n	=	density of the air in the nozzles	(kg/m^3)
ρ_1	=	density of the air in the suction	nozzle of
		the booster	(kg/m^3)

 Q_n = air flow rate over the nozzles (m^3/s)

12.2.2 Calculation of the air speed in the test ventilator

The air speed in the test ventilator is calculated from:

- at the suction nozzle

$$u_1 = Q_a / A_1$$
 (12.7)

- at the outlet:

$$\mathbf{u}_2 = \mathbf{Q}_1 / \mathbf{A}_2 \tag{12.8}$$

where:

u ₁	=	average	air	speed	in	the	suc	ction	no	zzle	of
		the boos	ter							(n	1/s)
แก	=	average	air	speed	d i	in 1	the	outle	et	of	the

$$Q_{a}$$
 = air flow rate of the booster (m³/s)

$$A_1 = \text{surface area of the suction nozzle of the booster}$$
 (m²)

$$A_{1} = \frac{\pi}{4} x D_{1}^{2} - \frac{\pi}{4} x d_{1}^{2}$$
(12.9)

 A_2 = surface area of the outlet of the booster

$$A_{2} = \frac{\pi}{4} \times D_{2}^{2} - \frac{\pi}{4} \times d_{2}^{2}$$
(12.10)

Diameters D1, D2, d1 and d2 are specified in Figure 2.5.





The test ventilator must be installed in the testing room according to Figure 12.5, in which the distances a and b to the wall of the room must be half of the external length.

If deflection blades are necessary, the effect of these blades must be recorded by a second set of measurements, whereby the specifications of the ventilator are redetermined with the deflection blades fitted. See 12.2.4 for more information.

If reversible ventilators are installed it is necessary to determine the specifications of the ventilator working in both directions. To take these measurements the test ventilator is installed in the testing room in the two ways shown in Figure 12.1.

12.2.3 Determination of the driving force of the test ventilator

The theoretical driving force of the booster can be calculated from the volume of air and the outflow rate found in the above-mentioned ways. See Chapter 7 "Calculation principle of longitudinal ven-tilation systems".

Theoretical driving force

The theoretical driving force is calculated as follows:

$$I_{nom} = \rho_2 \times u_2 \times Q_a \tag{12.11}$$

where:

 (m^2)

Loom	=	theoretical driving force of the boo	ster (N)
ρ_2	=	density of the air in the outlet	of the
		booster	(kg/m^3)
u ₂	=	average air speed in the outlet	of the
		booster	(m/s)
Q,	=	air flow rate of the booster	(m^3/s)

Measurement of the actual driving force

In addition to calculating the theoretical driving force of impulse ventilators it is also necessary to measure the actual driving force.

Two methods are commonly used to measure the actual driving force. The first method is based on the equilibrium of a suspended ventilator, the second method is based on the equilibrium of a booster mounted on a carriage. Both methods are acceptable for the determination of the driving force provided that the driving force is measured directly with an electronic pressure box. The permitted measurement error should not be more than $\pm 1\%$.

The "suspended" method is less accurate for the measurement of the driving force of boosters mounted with deflection blades because the outflowing air has a tangential force. The axis of the ventilator thus revolves in relation to the direction in which the driving force is measured. Therefore the measuring method which uses a carriage is better because this method gives more accurate results also for measurements of mounted deflection blades.

The methods are represented schematically in Figures 12.6 and 12.7. Both methods must produce results with an inaccuracy of maximum $\pm 1\%$. It is advisable to check the arrangement of the test setup before any measurements are taken. It should be possible to calibrate the setup in a simple way in the presence of the inspector.

The density of the air and the power consumption must be determined simultaneously during the measurement of the driving force in accordance with the method described in 12.5.2.



The pressure box is a measuring instrument from which the force of pressure as well as the intensity of the draught can be read (with zero adjustment)

FIGURE 12.6:

Measurement setup to determin driving force according to the "suspension" method

Further description of the "suspension" method

The test ventilator is suspended exactly horizontally from two chains on a support frame. The length of the chains must be at least 2 times the diameter of the ventilator fan. The point of attachment of the electronic pressure box onto the ventilator must not be displaced when the ventilator revolves. Displacement of this point affects the measurement. The driving force must be able to be read directly from the measuring instrument.

During this measurement there may not be any objects or walls within a distance of 7 to 8 times the diameter of the fan of the test ventilator on the suction and outlet sides of the test ventilator.

Further description of the "carriage" method

The test ventilator is attached to a carriage. The carriage has linear bearings with minimum friction. The friction force of the carriage with the ventilator mounted on it may amount to a maximum of 0.5% of the driving force to be measured.



The pressure box is a measuring instrument from which the force of pressure as well as the intensity of the draught can be read (with zero adjustment)

FIGURE 12.7:

Measurement setup to determine the driving force according to the "carriage" method

In this case measurement is also recorded by an electronic pressure box with a direct display. The point of attachment of the pressure box on the ventilator may not be allowed to affect the result of the measurement.

During this measurement there may not be any objects or walls within a distance of 7 to 8 times the diameter of the fan of the test ventilator on the suction and outlet sides of the test ventilator.

12.2.4 Determination of the effect of the deflection blades on the ventilator

To be able to check that the deflection blades are working properly measurements must be taken to determine the effect of the deflection blades on the volume of air, the power consumption and the driving force of the ventilator.

Determination of the effect on the volume of air

First of all the decrease in the volume of air of the ventilator as a result of the installation of the deflection blades must be determined. Measurement should be carried out according to the method described in 12.2.1. Non-reversible ventilators only have deflection blades fitted on the outflow side. The capacity is measured with and without deflection blades. Reversible ventilators have deflection blades fitted on both sides. The capacity is determined for both directions with and without deflection blades.

The power consumption must also be measured during the measurement of the air volume according to the method described in 12.2.5.

Determination of the effect on the driving force

To be able to determine the reduction in the actual driving force due to the deflection blades, the driving force should be measured with and without deflection blades. This measurement proceeds according to the method described in 12.2.3. The "suspended" as well as the "carriage" method are acceptable provided that the required accuracy is complied with. The required accuracy is obtained more easily with the "carriage" method. If the deflection blades have been fixed to the booster in a horizontal position and the outflow angle is directed vertically upwards, the "suspension" method can also give accurate measurements.

12.2.5 Capacity and efficiency

Measurement of moment of torque

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The power consumption of the ventilator shaft can

be determined in the laboratory by means of a brake mean effective pressure meter.

Electrical measurement of losses

To be able to record the revolving power of the shaft the bearing resistance and residual losses of an unloaded electric motor are determined electrically as follows:

$$P_{\rm r} = P_{\rm o} - 1.5 \ {\rm x} \ {\rm I_0^2} \ {\rm x} \ {\rm R_0} \tag{12.12}$$

where:

P _r	=	reduction in power due to bearing	resistance
		and residual losses	(kW)
P。	=	electrical power consumption ir	n an un-
		loaded motor	(kW)
I _o	=	current in an unloaded motor	(A)
R _o	=	resistance of motor circuit in an	unloaded
	•	motor	(Ohm)
	÷		

The power of the shaft of an unloaded electric motor is determined from:

$$P_{shaft} = (1 - \frac{S}{n_{nom}}) \times (P_{b} - P_{r} - 1.5 \times I_{b}^{2})$$

$$- 0,005 \times R_{b}$$
(12.13)

where:

P _{shaft}	=	revolving power of the shaft in	а
		loaded motor (kW	/)
S	=	slip of electric motor (-	-)
n _{standard}	=	nominal speed of revolutions (s ⁻	¹)
Pb	=	electric power consumption in a loade	d
		motor (kW	1)
P _r	=	reduction in power due to bearing re	;
		sistance and residual losses (kW	1)
I,	=	current in a loaded motor (A	(۱
R _b	=	resistance of motor circuit in a loade	ed
		motor (Ohn	1)

Measurement of starting current and starting time The starting current in the case of switching on an electric motor must be determined from the measurement of the strength of the current by using an oscilloscope connected to a recorder. The intensity of the starting current I_a expressed in A is defined as follows:

$$I_{a} = \frac{I_{peaktopeak}}{2}$$
(12.14)

The effective intensity of the current I_{RMS} expressed in A is calculated from this as follows:

$$I_{RMS} = \frac{I_a}{\sqrt{2}}$$
(12.15)

The starting time T expressed in s can be determined from the graph of the recorder by adding up the number of periods (n) from the start until the nominal intensity of the current is reached and dividing the total by 50:

$$T = \frac{n}{50}$$
 (12.16)

Calculation of the outputs

A distinction can be made between the *total* efficiency and the *aerodynamic* efficiency.

The *aerodynamic* efficiency can be defined as follows:

$$\eta = \frac{P_a \times Q_a}{P_{shaft}} \times 100$$
(12.17)

where:

η	=	aerodynamic efficiency of the	
		booster	(%)
p,	=	booster pressure	(Pa)
0	=	air flow rate of the booster	(m^3/s)
P _{shaft}	=	revolving power of a loaded	
		motor	(kVA)

Note

Equation (12.17) can be used up to a total booster pressure of 700 Pa.

The *total* efficiency of the ventilator can be defined as follows:

$$\eta \text{ tot } = \frac{P_{\text{air}}}{P_{\text{mains}}} \times 100\%$$
(12.18)

where:

 P_{air} = the dynamic power in the air at the outflow opening. In the equation:

(12.19)

where:

$$P_{air} = \frac{Q_a \times p_d}{1000}$$

$$Q_{a} = A_{2} \times u_{2}$$
(m³/s)
$$P_{d} = \frac{1}{2} \times \rho \times u_{2}^{2}$$
(Pa)

after substitution this gives:

$$P_{air} = \frac{1.2 \text{ x } A_2 \text{ x } u_2^3}{2000}$$
(12.20)

12.2.6 Ratio of driving force to power consumption

Besides the aforementioned two efficiencies the ratio of the measured driving force to the power consumption, expressed in N/kW, is important.

The aim of the manufacturer is to make a booster which has the largest possible driving force combined with the lowest possible power. The total performance of a booster is assessed on the basis of the ratio N/kW. A reversible ventilator with a ratio of 30 N/kW is a good booster. A value of 35 N/kW is an excellent booster.

The total performance is calculated from dividing the result of the driving force measurement by the power consumption according to:

$$P_{tot} = \frac{I_{measured}}{P_{mains}}$$
(12.21)

where:

P _{tot}	=	total performance (f	N/kW)
Imeasured	=	measured driving force of the	
		booster	(N)
Pmains	=	power consumption from power plying mains	sup- (kW)

12.3 DETERMINATION OF SOUND ENERGY LEVEL

12.3.1 General

The determination of the sound energy levels of equipment in principle occurs in a laboratory in an echo chamber or a "dead" chamber. The determination of the sound energy level of boosters in the aforementioned way is not feasible in practice because of the large dimensions and the high output rate involved. The method in which the sound energy levels are calculated from sound intensity measurements is more suitable. Possible sources of disturbance do not affect the results.

12.3.2 Determination of sound energy by taking intensity measurements

The method used to determine the sound energy level by taking intensity measurements is described in "Draft international standard ISO/DIS 9614–1" dated 29 December 1989. It is specified in this design standard that sound intensity measurements must be taken on a hypothetical surface near the source according to the "point method". Alternatively the measurements can be taken according to the "scanning method", which is quicker to implement. The correct choice of the hypothetical surface is important for sources which radiate a strongly direction-dependent sound.

The measured sound intensities should be corrected according to the recommendations made by the manufacturer of the measuring device. A real-time analysis is best in which all the correction calculations are carried out by means of the software. The measuring equipment must comply with the IEC standard.

To determine the sound energy based on intensity measurements it must be assumed that the hypothetical surfaces are round the sound source. This is presented diagrammatically in Figure 12.8.

Sound measurement of a tunnel ventilator. The Ventilator is in the centre of the imaginary box.



Note: measure end surface on the suction side of the ventilator 2x. The outlet side is not measured.

FIGURE 12.8:

Diagram of hypothetical surfaces

The intensity of the sound of each surface is measured perpendicular to the surface. The measurement of the intensity can be taken according to either the point method or to the scanning method (see Figure 12.9). Both methods are acceptable but to avoid discussion it is advisable to agree which method will be used before the measurements are taken.

The sound energy level at the surface is determined by multiplying the measured intensity at the surface area concerned. The total sound energy level of the source is obtained by adding up the sound energy levels of all the surfaces.



FIGURE 12.9:

Scanning pattern of the "scanning method"

12.3.3 Calculation

The sound energy levels are determined for each frequency band. All of which can be formulated as follows:

$$L_{WI} = 10 \times \log \left(\sum_{i=1}^{n_i} A_i \times 10^{0.1 \times L_{1i}}\right)$$
 (12.22)

where:

L _{WI}	=	sound energy level at frequency	I in
		relation to 10^{-12} W	(dB)
A _i	=	surface area of the hypothetical	sur-
-		face	(m^2)
т	_	cound intensity of frequency Land	0.0.5

L_{II} = sound intensity at frequency I and surface i in relation to 10^{-12} W/m² (dB) n_i = number of surfaces i (-)

12.4 CHECKING MEASUREMENTS TAKEN IN THE TUNNEL

12.4.1 General

After the ventilators have been installed, measurements should be taken in and around the tunnel to be able to determine the performance of the ventilation system. These measurements serve to check the calculations.

It must be constantly kept in mind that the conditions in which measurements are taken in the "field", such as tunnel measurements, do not affect the results without being monitored. The following factors can have an effect on the measurement results:

- meterological conditions
- possible obstacles in the form of scaffolding, and such like
- cars
- measuring equipment.

Most factors, with the exception of the meterological conditions, can be excluded by taking appropriate measures. Therefore measurements can only be taken in good weather conditions. Before starting to take measurements the meterological conditions (air pressure, temperature, wind effect) should be established, on the basis of which the decision is taken as to whether the tunnel measurements should be taken. See 12.5 "Other conditions during the measurements".

To enable the calculation of the effect of traffic to be checked measurements with various compositions of traffic are required. In addition not only the resistance of stationary traffic but also that of travelling traffic at different speeds should be measured. Such measurements of traffic are very extensive and therefore time consuming and expensive. It is therefore usual to omit the checking measurements of the effect of traffic. It is assumed that if the measurement results *without* traffic match the corresponding calculation results, the calculation method for the calculation *with* traffic is sufficiently reliable.

All the measurements described below refer to an empty tunnel tube, in which there is no or hardly any wind effect.

12.4.2 Reversible/nonreversible longitudinal ventilation system

The performance of the nonreversible ventilation system is only determined for the normal direction of

ventilation. For a reversible system all the measurements must be taken with the system working in the normal ventilation direction as well as in the opposite ventilation direction.

This means a doubling of the number of measurements. It may be necessary to limit the number of measurements in order to make savings or for other reasons. It is frequently the case that measurements have been planned but due to weather conditions cannot be carried out or must be stopped when the measurements are being taken. In these cases it is advisable to at least carry out all the measurements as described above of the system working in the normal ventilation direction. It may be possible to omit those measurements of the system working in the opposite direction which concern speed distribution and the effect of the deflection blades .

12.4.3 Measurement grid

To be able to determine the average air speed and the speed distribution in a tunnel cross section, to in so doing be able to calculate the volume of air, the speed measurements are taken at various points on a measurement grid. An anemometer with an electronic averaging device over a time interval of 40 s is used to take these measurements. The air speed is determined from the arithmetic mean of the number of measured values.

The air speed is measured on the grid points of a measurement grid at the chosen place of measurement, so that the grid fits into the cross section in such a way (see Figure 12.10) that the width and height are divided into a number of identical rectangles, with as grid measurements:

- widthwise 1.0 to 1.5 m
- heightwise 0.5 to 1.0 m.

The points of measurement near the walls lie at half the grid distance, with the understanding that the distance to the road surface, the walls and the ceiling is at least 0.5 m.



The size of the grid measurements must always be in proportion to the measurements of the tunnel. A larger number of grid points gives a more accurate measurement result but the time involved to take the measurements is much longer. Therefore on practical grounds the following grid measurements are recommended for Dutch tunnels:

- for a two-lane tunnel approx. 1.0 m for the width and 0.75 m for the height
- for a three-lane tunnel approx. 1.5 m for the width and 0.75 m for the height.

12.4.4 Checking measurements to be taken in the tunnel after installation

After the ventilators and the other systems have been installed and the construction of the tunnel is finished, tunnel measurements are taken in the tunnel tube without traffic to assess the performance of the total ventilation system and to check the calculations. The following factors are considered or they are determined by measurement:

- the effect of the longitudinal ventilation system
- the effect of wind
- the displaced volume of air

- the air speed distribution over the cross section profile

- the inflow and outflow resistances
- the tunnel resistance
- the effect of the deflection blades
- the sound energy
- the total efficiency.

12.4.5 Effect of the longitudinal ventilation system on the measuring method/place of measurement

Interference effects caused by the ventilation system

which could affect the measurements should be taken into account. The way in which the longitudinal ventilation system is realized also determines the way in which the checking measurements in the tunnel are taken. A distinction can be made between longitudinal ventilation by boosters distributed over the length of the tunnel and longitudinal ventilation by an injector. A combination of both systems is also possible. (See Chapter 5 for more information).

In a ventilation system with boosters distributed over the length of the tunnel the air speed measurement can only be taken accurately in front of the first booster which is working. The inflow effects of the tunnel tube must be taken into account here. The inflow effects do not operate at a distance of $10 \times D_h$ m into the tunnel from the entrance opening. This means in practice that the best place for measurement is past the first booster. To be able nevertheless to take an accurate measurement it is necessary to either switch off the boosters in front of this measuring point or to accept a shorter distance from the entrance opening. This distance must not be shorter than 5 x D_h m.

In an injector system, in an open as well as a closed design, it is not possible to take accurate measurements in the injectors's area of influence, the effect of which is noticeable over a distance of a few hundred metres. In the case of the application of such a system the air speed measurements must be taken in a cross section as far away from the injector as possible, for example 25 m from the tunnel entrance opening.

In a combined system, namely an injector and boosters distributed over the length of the tunnel, measurement of the air speed cannot be taken very well because the speed profile is affected by the boosters or the injector in the vicinity of the measurement cross section. By switching off several ventilators in the vicinity of this place this effect can be reduced to such an extent that it is possible to take an acceptable measurement. The distance from the last booster which is working should be 100 to 150 m. Especially in shorter tunnels the number of the remaining boosters distributed over the tunnel can be too small to obtain a good picture of the performance of the combined ventilation system.

No experience has been had of the combined system in the Netherlands because it has only recently been decided to apply this type of system. A solution to the measurement problem could be found by measuring both systems separately and determining the eventual performance of the whole system by calculation. In that case measurement can be accurate and the calculation method determines the extent to which the results represent the actual situation.

12.4.6 Measurement of the effect of wind

The speed and the direction of the air in the tunnel tube, caused by the wind, are measured with the ventilators switched off. The place where measurements are taken in the tunnel is $10 \times D_h$ m from the entrance opening. In this cross section the air speed generated by the wind is measured in each case before and after a series of measurements. The air speed is measured according to the measurement grid of Figure 12.10. The arithmetic mean is determined of the measured air speeds.

No measurements should be taken if the air speed in the tunnel tube caused by the wind, measured according to 12.4.3, is more than 1 m/s. At lower speeds the measurement values should be corrected as follows:

- with the wind in the same direction:

$$\mathbf{u}_{\text{corr}} = (\mathbf{u}_{\text{measurement}}^2 - \mathbf{u}_{\text{wind}}^2) \tag{12.23}$$

- with wind in the opposite direction:

$$\mathbf{u}_{\text{corr}} = (\mathbf{u}_{\text{measurement}}^2 + \mathbf{u}_{\text{wind}}^2)$$
(12.24)

where:

u _{corr}	=	corrected air speed	(m/s)
Umcasurement	=	measured air speed with	th ventilators
		working	(m/s)
u _{wind}	=	measured air speed as	s a result of
		wind	(m/s)

If there is a difference between the average measured air speed, due to the wind effect, before and after the series of measurements, the arithmetic mean must be taken for u_{wind} .

If there are two tunnel tubes, at the same time as the measurement of the air speed is being carried out in one tunnel tube the air speed can be measured and recorded at a reference point in the other tunnel tube. Such a reference measurement should be carried out with the necessary caution. It is known from measurements of models taken by NLR (National Air and Space Laboratory) that the effect of the direction of the wind can give very different results because in the one tube a clearly different effect of the wind is encountered than in the other tube. It is assumed in the reference measurements that the shape factor in combination with the wind direction is the same for both tunnel tubes. This is often not the case so it is not advisable to take these reference measurements without taking the aforementioned effects into account.

If there is only 1 tunnel tube available, then the wind speed must still be checked as stated above before and after the measurement is taken. The static pressure difference in and outside the tunnel can be recorded continuously also during the measurement of the air speed. This recording provides a second possibility of checking the wind effect during the measurement of the air speed.

12.4.7 Measurement of air speed in the tunnel,

calculation of the displaced volume of air Since the volume of air displaced by the ventilation system cannot be directly measured but is calculated from the air speed and the surface area of the cross section, the following comments are important:

- a. The cross section must be chosen at the place where the speed is also determined. This is not a problem in tunnels with a uniform cross section. However, in tunnels with a cross section which is not uniform down the length of the tunnel but which deviates by having for example a lane for slow-moving traffic which begins in the tunnel, the place where the measurements are taken must be considered carefully.
- b. In a longitudinal ventilation system with boosters distributed over the length of the tunnel there are not usually any inflow effects in the cross section at 10 x D_h m from the entrance opening. This means for example in the Zeeburg tunnel that where $D_h = 7.2$ m the distance to the entrance opening is 72 m. Normally speaking there are several boosters in the first part of the tunnel which interfere with the constant speed pattern so that it is not possible to take an accurate speed measurement. Therefore either a shorter distance from the entrance opening must be accepted or the ventilators in this part of the tunnel must be turned off. The solution chosen should be determined before the guarantee measurements are started to be taken.
- c. If an injector has been installed, the distance

between the injector and the place of measurement should be as large as possible but at least 250 m. The best place to take measurements is 25 m in front of the exit opening.

- d. A prerequisite for an accurate determination of the capacity is that the speed distribution in the cross section where the speeds are measured is even. If the speeds measured at the grid points deviate from each other by more than 5%, then the measurements taken are no longer reliable.
- e. If the wind effect is too great, it is not possible to take an accurate speed measurement due to the unstable nature of the wind.

It is advisable to use an anemometer, which has an electronic averaging device over a time interval of a minimum of 40 s.

Calculation of the displaced volume of air

The air flow rate in the tunnel tube is calculated from:

$$Q_{t} = A_{t} \times \frac{1}{n_{m}} \Sigma u_{corr}$$
(12.25)

where:

Q	=	air flow rate in the tunnel tube	(m ³ /s)
A	=	surface area of the cross section	of the
		tunnel tube	(m ²)
n _m	=	number of measurements	(-)
Σu_{corr}	=	sum of the corrected air speeds	in the
		tunnel tube	(m/s)

Place of the measurement: preferably 10 x D_h m from the tunnel entrance opening and at least 5 m before the inlet side of the first ventilator which is operating. In this cross section the average speed is measured according to the method described in 12.4.3. The arithmetic mean is determined of the measured air speeds. The calculation of the capacity proceeds by using equation (12.25) as give above.

It is recommended that the air speed is determined by taking speed measurements near different numbers of ventilators which are operating. For a system with boosters a good impression of the effect of the number of boosters (and thus the ventilator capacity) on the air flow rate in the tunnel tube can be obtained by measuring:

- all the ventilators which are working, working in the normal direction that is in the same direction

as the traffic

- two-thirds of the number of ventilators which are working, working in the normal direction
- one-third of the number of ventilators which are working, working in the normal direction.

In a reversible longitudinal ventilation system with boosters the capacity must also be determined in the opposite ventilation direction in the same way as given for the normal direction. Thus the air speed is also measured in the opposite direction for three different proportions of boosters working, from which the air volume is calculated.

The effect of the capacity of the ventilators on the air flow rate in the tunnel tube can be determined in a similar way for a ventilation system with an injector. If the injector is supplied by several ventilators, the capacity can be adjusted by switching ventilators on and off. If the injector is supplied by only one ventilator, it is possible to alter the output of the ventilator by the blade setting or the speed regulation so that also in this case the relationship between ventilator capacity and displaced volume of air can be determined.

A good idea can be had of the relationship between the capacity of the ventilators and the displaced volumes of air in the system by presenting the results in a graph. This information says something about the quality of the total ventilation system including structural aspects.

12.4.8 Measurement of the air speed distribution in the tunnel

To obtain a good impression of the speed distribution over the length and width of the tunnel the speed distribution must be measured at various places in the cross section of the tunnel tube.

The air speed distribution is measured under the following conditions:

- empty tunnel, therefore no scaffolding, cars, etc
- a minimum of half the number of ventilators working, the ventilators should be working continuously
- the ventilators displace the air in the direction normally travelled by the traffic
- the places where measurements are taken in the tunnel tube are calculated from the outflow opening of the last ventilator which is working in a downstream direction and are 5, 25 and 50 m from this point (see Figure 12.11).
- air speed checking measurements are taken at 10

- $x D_h$ m from the entrance opening
- the resulting wind effect in the tunnel tube may not create higher wind speeds than 1 m/s. The direction of the longitudinal current generated by the wind should preferably be in the same direction as that of the ventilation.

The speed measurements at the measurement points as well as the checking measurements should be taken on the grid points of the measurement grid according to Figure 12.10.



Note: a minimum of 50% of the ventilators working

FIGURE 12.11:

Measurement points shown in the longitudional direction

After the speed distribution measurements have been taken the average speed in the various cross sections must be compared to the average speed from the checking measurement. The average speed is obtained by calculating the arithmetic mean of the measurement results in the different cross sections and should not deviate from each other by more than 5% of the value of the checking measurement. If the deviation is larger than this the measurements should be taken again.

If there are reasons to suppose that the air speed distribution for the opposite ventilation direction may differ to a considerable extent, the speed distribution should also be measured in a similar way to that described above. A reason for such a measurement being taken could be a widening or a narrowing of the cross section of the tunnel tube.

12.4.9. Measurement of inflow and outflow losses

Since knowledge about the inflow and outflow losses is limited and there is a lack of correct measurements taken according to a standard procedure, it is recommended that as soon as each tunnel is completed and before it is opened to traffic the inflow and outflow coefficient is determined by means of taking measurements. The purpose of these measurements is to give an impression of the actual losses to be able to check the assumption made with respect to these coefficients during the design stage.

The measurement points chosen must not be affected by thrusting pressures as a result of wind or moving traffic in the vicinity of the measurement point. In practice it appears that this type of measurement is difficult to take, if there is too much wind. Also the effect of moving goods vehicles must not be underestimated when measurements are being taken. These measurements are therefore taken in an empty tunnel tube.

The measurement points for the measurement of the pressure difference are located at a point at least 60 m from the tunnel opening outside the tunnel tube and 10 x D_h m into the tunnel tube. The pressure is measured along the axis of the tunnel tube and along the extension of this outside the tunnel at a height of 0.5 m above the road surface.

The measurement of the pressure difference proceeds as follows:

- the pressure is recorded at both measuring points and converted by a transducer to an electrical signal of 0-20 mA
- the electrical signal is sent to a suitable recorder
- the rate at which the paper goes through the recorder is such that the peaks and troughs of the pressure at each measurement point can be distinguished easily.

The measurement of a pressure difference taken with a oblique tube manometer which measures the pressure difference between the two measuring points by means of hoses gives results which are difficult to interpret because of the time delay in the hoses. A measurement taken in this way is definitely not to be advised.

The measurement of the inflow and outflow coefficient proceeds as follows. To obtain reliable coefficients the following recommendations have been formulated:

- take this measurement in almost calm weather. The maximum wind speed near the outside measurement point is 1 to 2 m/s
- record the difference in pressure automatically for a measurement time of at least 40 s the average of which is calculated electronically
- record the values thus obtained by means of a recorder

- the inflow and outflow rate must be at least 3 m/s, preferably higher. Take the measurement of at least 2 different inflow and outflow rates
- convert the measurement results into a coefficient and take the arithmetic mean of these thus calculated coefficients.

12.4.10 Measurement of the tunnel resistance

The tunnel wall creates a resistance due to the roughness of the wall and the equipment installed in the tunnel. To be able to calculate this resistance better in the future a checking measurement should be taken. The measurement must be taken according to Figure 12.12.



FIGURE 12.12: Measurement of the tunnel resistance

- the pressure is recorded on both measurement points and converted by a transducer into an electronic signal of 0 – 20 mA
- the electronic signal is sent to a suitable recorder
- the rate at which the paper travels through the recorder must be such that the peaks and troughs of the pressure can be distinguished easily at both measurement points.

To obtain reliable pressure difference results the following recommendations have been formulated:

- take this measurement in almost calm weather. The maximum wind speed near the outside measurement point is 1 to 2 m/s
- record the difference in pressure automatically for a measurement time of at least 40 s the average of which is calculated electronically
- record the values thus obtained by means of a recorder
- the inflow and outflow rate must be at least 3 m/s, preferably higher. Take the measurement at a minimum of 2 different air speeds
- convert the measurement results into a coefficient of wall friction and take the arithmetic mean of these thus calculated coefficients
- the distance between the measurement points

should be preferably 300 m but a minimum of 200 m.

12.4.11 Measurement of the effect of deflection blades

If deflection blades have been fitted to increase the positional efficiency of the ventilation system, air speed measurements must be taken *with* and *without* deflection blades to determine the difference in the displaced volume of air.

Measurement proceeds according to 12.4.7. To gain a good impression of the operation of the deflection blades this measurement must be taken with at least 30% of the ventilators working.

12.4.12 Measurement of the sound level in the tunnel

To assess the sound production of the axial flow fans in the tunnel sound checking measurements should be taken.

The sound measurements should be taken under the following conditions:

5 m

- empty tunnel tube

- no or hardly any wind effect from outside (u_{wind}
 1 m/s)
- air temperature in the tunnel between 11 and 31°C
- minimum number of axial flow fans which are directly after each other and are working is 7
- the ventilators displace the air in the direction normally travelled by the traffic
- the measurement points are as indicated in Figure 12.13
- the measuring equipment should fulfil the conditions specified in the instructions for the measurement and calculation of industrial noise (IL-HR-13-91).

The average sound level in dB(A) in the tunnel tube should be determined as follows from the total number of measurements taken:

$$L_{P_{a}} = 10 \text{xlog} \sum_{m=1}^{n_{m}} \left(\frac{L_{P_{a} m/10}}{n_{m}} \right)$$
 (12.26)

where:

L _{Pa}	=	averag	e sound i	intensity	leve	l (dB(A))
L _{Pam}	=	sound	intensity	level a	t the	measurement
		point				(dB(A))
		•	<u>^</u>			(0.5)

 n_m = number of measurement points (25)



FIGUUR 12.13:

Measurement points to determin the sound level of the axial flow fans in the tunnel

12.4.13 Measurement of total efficiency

By determining the total efficiency one can obtain an impression of the quality of the whole ventilation system including the structural implementation.

The total efficiency of the system is understood to mean the quotient of the kinetic energy in the circulating air and the electric energy consumed from the power supplying mains.

By defining the efficiency of the ventilation system in this way discussion is prevented about all sorts of aspects which are difficult to measure in practice. Because the measurement of the air speed as well as the power consumption from the mains have been clearly defined, different tunnels can be compared with each other.

$$\eta_{tot} = \frac{P_{air}}{P_{mains}} x 100$$
(12.27)

where:

 $\eta_{tot} = total efficiency of the ventilation syst (%)$ $<math>P_{air} = kinetic energy transferred to the tunnel$ air (kW) $<math>P_{mains} = power consumption from the power sup$ plying mains (kW)

 P_{mains} must be measured near the main distributor. Possible step-up step-down facilities are therefore also measured and are therefore included in the losses.

The kinetic energy in the tunnel air is given by:

$$P_{air} = \frac{Q_{t} \times P_{d}}{1000}$$
(12.28)

where:

$$Q_t = A_t x u_t \qquad (m^3/s)$$

Pd = ½ x $\rho x u_t^2$ (Pa)

After substitution it follows that:

$$P_{air} = \frac{1.2 \text{ x } A_{t} \text{ x } u_{t}^{3}}{2000}$$
(12.29)

The speed u_i should be measured according to 12.4.7.

By comparing the total efficiency of the system with and without deflection blades, the effect of the deflection blades can be worked out easily.

If one wants to determine where the losses occur and how these arise, a measurement programme must be drawn up for each tunnel.

12.5 OTHER CONDITIONS DURING THE MEASUREMENTS

12.5.1 Measuring equipment

The air speeds must be measured with an anemometer, which has been calibrated no longer than 6 months ago. The measurements must be averaged automatically over an adjustable measurement time of 40 s.

To enable the air speed measurements to be taken easily and quickly, the anemometer is attached to a telescopic measuring stick which is 5 m long so that the correct height of the place where the measurement is taken can be determined.

12.5.2 Deviation from the standard conditions All measurements are based on an air density of 1.2 kg/m³. Errors of -9.75% and +10.25%, respectively will arise if the values deviate from this air density by -5% and +5%. Therefore measurements may be taken without corrections being necessary afterwards, if the density lies between 1.16 and 1.24 kg/m³. This requirement must be checked during the measurement to see if it has been met. This is the case at air temperatures between 11°C and 31°C and the normal air humidity.

By measuring the wet and dry bulb temperature and plotting these values on a psychometric chart the density of the air can be determined graphically. If the barometric pressure deviates by more than 5% from the pressure for which the psychometric chart has been drawn up, the density must be determined by being calculated from measurements of pressure, temperature and humidity as given in equation (12.30):

$$\rho = 0.002167 \text{ x} \frac{1 + x}{(t + 273.15) \text{ x} (0.662 + x)} \text{ x } p_{b}$$

where:

ρ	=	density of the air	(kg/m^3)
t	=	air temperature	(°C)
x	=	absolute humidity	(kg/kg)

 $p_b = air pressure$ (Pa)

$$p_b = p_o x e^{-\frac{0.0035 x g x H}{t + 273.15}}$$
 (12.31)

where:

p _o	=	air pressure at sea level	(Pa)
Η	=	height above sea level	(m)
g	=	gravitational acceleration	(m/s ²)
g	=	$9.780373(1 + 0.0052891 \text{ x sinB})^2$ -	- 0.0000059
		$x \sin^2(2B)$	(12.32)

where:

(°)	
	(°)

12.5.3 **Other comments**

The tunnel tube(s) must be free of traffic and obstacles when the measurements are taken.

To prevent deviations in the measurements from arising as much as possible a sufficient number of checking measurements of the wind effect must be taken to ensure that this effect is kept to a minimum when taking the series of measurements.

The check on the wind speed should be made directly before as well as after each measurement series.

To prevent misunderstandings about reliability values, it is wise to set down in the construction specifications and the agreement the way in which and with which permissible deviations the measurements should be taken.

12.6 PERMISSIBLE DEVIATIONS WITH RES-PECT TO THE SPECIFICATIONS

Table 12.1 gives an overview of the permissible deviations from the specifications.

Table 12.1:

Permissible deviations

subject	laboratory measurement	tunnel measurement
air volume driving force density power consumption speed of revolutions sound energy pitch filtering starting current starting time	± 2% ± 1-2% ± 1-2% ± 0,5% ± 3 dB ± 5 dB ± 5 dB ± 5%	± 5% n.v.t. ± 3% ± 5% * not used ± 5 dB ± 7 dB ± 5-10% * ± 20-25% *

13 MEASUREMENT SYSTEMS AND CON-TROL SYSTEM

(H. Speulman and L. Swart)

13.1 GENERAL

For the control of the ventilation system the following measurements must be taken in a tunnel tube:

- the CO concentration

- the smoke concentration

- the speed and direction of the air in the tunnel tube

- the temperature of the air flow

- the wind speeds on the entrance and exit openings.

The concentration of other dangerous gases is not measured for the moment.

In the case of longitudinal ventilation the measurement of the direction of the air flow in the tunnel tube is used as a control signal for controlling the direction of ventilation. This can only occur in the case of transverse ventilation, if measures have been taken to control the longitudinal current. If no measures have been taken, then the measurement of the direction of the air flow in the tunnel tube supplies useful information to the control room and the fire brigade.

13.2 MEASUREMENT AND RECORDING OF CO CONCENTRATION

The ventilation system is controlled based on the measurement of the CO concentration in the tunnel air.

There are various systems for measuring the concentration of carbon dioxide. A chemical analysis system with a hopcalite cell has been chosen for the tunnel ventilation systems because of the proven reliability of the system in practice. The equipment can be set up in the middle of short tunnels. In longer tunnels it is perhaps necessary to set the equipment up in a decentral position because the suction length of the sampling system is limited.

The measurement system consists of a processing unit set up in the control buildings and the sampling system or suction system. The sampling system consists of one or more suction pumps which continuously draw in tunnel air at the installed sampling points. The sampling points are regularly connected up to the analysis equipment through a distribution device. The sampling time, or the time which elapses between taking a sample and processing it into a measurement signal, is determined by the rate of flow in the suction lines and the chosen cycle time of the analysis. Since the rate of flow is limited, the sampling time can be too long with longer suction lines. This can be overcome by placing the analysis equipment decentrally at short distances from each other.

For the tunnels in the Netherlands with a longitudinal ventilation system the usual places where samples are taken are at 1/5 of the tunnel length from the tunnel entrance opening, at 1/2 of the tunnel length and at 1/5

of the tunnel length from the tunnel exit opening. This arrangement is also suitable for two-way traffic.

The equipment must comply with the following specifications:

- measuring range: 0-400 ppm CO in air
- maximum acceptable scale value: 500 ppm CO in air
- maximum response time: 1 minute for 90% of the scale value
- temperature range: -17°C to +50°C with an electronic stability of 1 ppm below 100 ppm scale value and above this 1% of the scale end value
- measurement inaccuracy: ± 1 ppm below 100 ppm and above this ± 1% of the scale end value
- sensitivity to air humidity: for relative air humidities of 20 to 100% the maximum permissible deviation is: 2 ppm for scale values upto 10 ppm and above this 2% of the scale end value
- measuring sensitivity: changes in the CO concentration of the air of 1 ppm or less must be able to be detected
- connection voltage: 220 Volts, 50 Hz.

The equipment must not react to petrol fumes or other substances which can occur in the exhaust fumes.

The suction filter must be separately attached to the suction line and be capable of being changed quick-ly.

The output signal must not affect the ventilation control during the time that the analysis equipment is warming up. The analysis must have a built-in zero calibration system.

The measurement signals given by the CO analysis equipment are averaged in a control box and sent to a processing unit which can be set at a maximum of 5 switch steps for the ventilation. The setting of the switch steps, each with an adjustment range of 0 to 400 ppm, must be simply arranged and easily readable. The measurement results are recorded by means of two single dotted line recorders, one for each tunnel tube.

The CO measurement is necessary to switch on the ventilators as soon as the CO concentration in one tunnel tube reaches the set or lowest recommended value. The reader is referred to the guidelines in Chapter 6 "Permissible levels of air pollution".

13.3 MEASUREMENT AND RECORDING SMOKE CONCENTRATION

Smoke in a tunnel tube is mainly caused by diesel engines. The concentration of which must always be measured by means of an optical system. Labyrinth dust rings are fitted inside the measurement tubes to prevent the measurement system from becoming polluted.

Visibility measuring equipment must be installed in two places in each tunnel tube, namely in the middle and at the end, viewed in the normal direction of the traffic.

The following specifications apply to the measurement equipment:

- type of equipment: photo-electric visibility measuring equipment, including dust protecting tubes suitable for a measuring range transmission of 0-100%, with reflector for a measurement distance up to a maximum of 40 m
- reflector without electrical connection
- diameter of the objective: 100 mm
- average life of the lamp: 10,000 burning hours
- design: dust and drip-proof.

The optical measuring head and the reflector must be attached by brackets to the wall or the ceiling of the tunnel tubes. Neither the equipment nor the light beam emitted may be located in the clearance space profile in the tunnel tubes. When the optical measuring head is installed in the tunnel the accessibility of the inside of the equipment for adjustment and for normal maintenance must be taken into account. The signal cables must be covered.

Both measurement signals sent by the two optical measurement heads in the tunnel tube are averaged in a control box and sent to a processing unit which can be set at a maximum of 5 switch steps for the ventilation. The setting of these switch steps, each with an adjustment range of 0 to 100%, must be simply arranged and easily readable.

Two single dotted-line recorders are required for the visibility measurements, one for each tunnel tube. The measurement signal must be recorded separately for *each* measurement point.

The ventilation is switched on at a permissible deterioration in visibility k_t as described in 3.6.

13.4 MEASUREMENT OF RATE AND DIREC-TION OF THE AIR FLOW

In each tunnel tube the rate and the direction of the air flow must be measured at one place by means of 2 "air flow sensors": one air flow sensor for the ventilation in the normal direction of the traffic and the other for the opposite direction. These air flow sensors should preferably be installed on the ceiling of the tunnel and certainly in the middle of the tunnel tube.

In the normal operating system the measurement signal is inputted into an electronic processing unit which controls the direction and capacity of the ventilation system. In addition the measurement signal must be made visible in the control room so that in the event of fire the direction of ventilation can be reversed and or the capacity adjusted.

13.5 MEASUREMENT OF THE TEMPERA-TURE OF THE AIR FLOW

In the case of fire in the tunnel it is important for the control room and the fire brigade to know the temperature of the tunnel air. As explained elsewhere in these recommendations the temperature decreases with the distance from the source of the fire. To be able to follow this decrease PTC resistances are installed inside suitable housing at three places in the tunnel tube. These places should correspond to the sampling points for the measurement of CO (see 13.2).

It can be considered if the thermistor temperaturemeasuring device is necessary. The costs of this safety system and the fact that the bridging of this system during a fire forms a weak connection, can be reasons not to consider this type of safety system.

13.6 MEASUREMENT OF WIND PRESSURE ON THE TUNNEL OPENINGS

By measuring the wind pressure differences over the openings one can determine in which direction the ventilation should be to obtain the maximum air speed in the tunnel tube. This means in the same direction as the wind as much as possible, irrespective of the direction of the traffic. This measurement, together with the air speed and direction of the tunnel air, gives a decisive answer to the choice of the direction of ventilation. The electronic control unit supplies this signal to the control unit of the ventilation system and the control room.

Although the automatic control of the ventilation system is switched off during a fire the information is especially important during a fire.

A total of eight pressure recorders are installed in the walls of the control buildings to measure the wind pressure differences: two at the beginning and two at the end of each tunnel tube. Within the building inductive pressure difference recorders must be installed at the stated places with a measuring range of $0-100 \text{ N/m}^2$. The pressure recorder must be supplied with a replaceable dust filter on the reference pressure side. The length of the recorder with dust filter should not be longer than 100 mm.

The measurement signals from the installed pressure recorders are first averaged in a control box for each tunnel tube separately. These averaged values are subsequently converted into a pressure difference between the openings of the tunnel tube and inputted into an electronic control unit.

13.7 CONTROL OF THE VOLUME OF VEN-TILATION AIR

Groups of 4 to 5 boosters in each group are "fired off" for each tunnel tube. The cutting in of the booster groups takes place on the basis of the first four switch steps of either the CO or the visibility measuring equipment. In principle the boosters blow air in the same direction as normal direction of the traffic.

The following signals are processed in the general control unit:

For cutting in the booster groups:

- the switch steps of the CO measurement (4 switch steps)
- the switch steps of the visibility measurement (4 switch steps)
- the information signals "working" from the booster groups
- the information signals "not working" from the booster groups
- the air temperature measurement signal.

For choosing the ventilation direction:

- the alarm signal at the max. CO concentration (5th switch step)
- the alarm signal for minimum visibility (5th switch step)
- the signal of the wind pressure difference measurement over the tunnel openings
- the signal of the measurement of the rate and the direction of the air flow in the tunnel tubes
- the signal that indicates if two-way traffic is allowed in the tunnel tube.

The general control unit indicates via the control panel that it is desirable to reverse the direction of ventilation of the boosters. If desired the control unit can control the ventilation direction automatically or the tunnel control room operator can give a switch command to this effect.

Two information signals can be returned to the battery cable terminals of the control box indicating whether or not the booster group is already switched on.

13.7.1 Switch logic

As soon as the first switch has been cut in based on the CO or visibility measurements, the measurement system used to determine the direction of ventilation must be activated. In which case it is first of all checked if the measured wind pressure difference over the tunnel openings is higher than the wind pressure difference set. Calculations show that the wind pressure difference to be set must be about 30 N/m². The adjustment is carried out by using for example a potentiometer with an adjustment range of 0 to 100 N/m². The correct adjustment value must be determined while in operation.

If the measured wind pressure difference is higher than the set value, then the rate and the direction of the air flow must be determined in the tunnel tube.

If the measured air speed is in the opposite direction to that of the traffic and in addition exceeds a certain preset value, a signal must be sent to the control panel and the control unit or the control room operator reverses the direction of ventilation. In the case of fire in the tunnel the automatic control of the direction of ventilation is put out of operation and the preferred situation of the same direction as the normal direction of the traffic is engaged.

The air flow value to be set must be adjustable within the limits similar to the average air flow rates of -10 to +10 m/s.

After the direction of ventilation of the boosters has been determined, if necessary by the intervention of the tunnel control room operator, the first group of boosters is put into action. If the CO or smoke concentration continues to rise the next switch step is switched over to in a step-wise way which then drives the next group of boosters. If the concentration falls, one booster group at a time is cut in or cut out in a step-wise fashion. To avoid the situation arising that a booster group is cut in or out in the case of a short-lived rise or fall in the concentration, the cutting in or out only takes place after a time delay of between 0 and 120 s after a switch step has been exceeded or gone below. If the 5th switching on step is exceeded while all the boosters are cut in an alarm must be given – after a time delay – to the control room. At the same time the chosen ventilation direction is checked auto– matically to see if it is still correct. The measured air flow rate in the tunnel tube is compared with the value (to be set) which can be expected in a ven– tilation system which is completely switch on. The tunnel control room operator must now take ap– propriate measures (for example closing off the tunnel tube).

If the air flow rate is lower than the required value, then this is an indication that the ventilation direction is not correct. If the tunnel is ventilated in the direction of the traffic, the wind pressure difference between the tunnel openings is checked automatically to see if it has become higher than the wind pressure difference set. If this is not the case, the direction of the ventilation is correct.

If the wind pressure difference between the openings is higher than the set value, the electronic control system or the control room operator gives a signal that the ventilation direction must be reversed.

At the same time that the signal "reverse ventilation direction" is given all booster groups are cut out. After the control unit or the control room operator gives the command to reverse the direction of the ventilation, the booster groups are automatically cut in consecutively. The groups are cut in with a time delay to avoid peaks in the flow.

14 ENVIRONMENTAL AND SAFETY AS-PECTS (N.P. Costeris and L. Swart)

14.1 GENERAL

The outside air contains a large number of dangerous substances as a result of industrialization and high concentrations of road traffic. The most important of these substances are measured constantly: sulphur dioxide (SO₂), nitrogen dioxide (NO₂), ozone (O₃) and carbon monoxide (CO). The effects of these pollutants on health and the acceptable limt values in and around tunnels has already been described in Chapter 6 " Permissible levels of air pollution".

The concentrations of dangerous substances are frequently many time higher in road tunnels than the limiting values applying to the outside air. These higher concentrations are considered acceptable within certain limits for a short stay. Depending on the situation specific air quality requirements are made. (See 6.6).

A longitudinal current will be present in the normal operating situation in tunnels with the usual length for the Netherlands, irrespective of the ventilation system. Due to the suction effect of the traffic a longitudinal current will be created, especially in tunnel tubes with one-way traffic, which leaves the tunnel tube through the exit and pollutes the surrounding area more by discharging dangerous substances. In general the nitrogen dioxide concentration is the determinative substance for additional measures. The concentration of carbon monoxide sometimes makes it necessary to take measures.

14.2 LOCAL AIR POLLUTION

Local air pollution is understood to mean the increased concentration of polluting substances which occur near the entrance and exits of road tunnels and in the vicinity of the possible polluted air shaft. The traffic as such does not produce any more pollutants than on an equivalent road of the same length and with the same difference in levels. The difference lies in the fact that the pollution in the tunnel only occurs in a small volume of air and therefore produces relatively high concentrations which are only lowered by being diluted with clean air outside the tunnel. In longer tunnels and an increased density of traffic the pollution of the environment reaches more serious proportions. The ventilation system chosen as well as the extent of the pollution of the environment is also strongly dependent on the shape and location of the tunnel. In addition wind force, wind direction and degree of turbulence have a great effect on this.

In general it can be assumed that habitation at a distance of 100 to 300 m from the entrances and exits of road tunnels 1 to 2 metres long and a traffic intensity of 10 to 50 thousand vehicles per day, carries a certain health risk. Should this occasion arise special measures should be taken. A solution to this problem is a tall outlet shaft out of which the polluted air is blown vertically at high speed. Due to the high outlet speed of polluted air mixing with relatively clean air occurs due to induction. The concentration of the polluting substances decreases sharply due to this dilution. This effect is increased even more by diffusion. Dilution by a factor of 100,000 is possible. Furthermore the polluted tunnel air only comes into contact with the surface of the earth a few kilometres away from the shaft, so that the pollution is spread over a large surface area. The increase in concentration of the general pollution already existing in this area will be hardly measurable because of diluting and spreading the tunnel pollutants.

The optimum position for an extraction shaft in tunnels with one-way traffic is near the exit opening because the polluted air is driven in this direction by the suction effect caused by the vehicles. In a tunnel tube with two-way traffic the best position for the extraction shaft is in the middle of the tunnel tube, whereby fresh air flows into the tunnel tube through both tunnel openings. It is often not possible for practical reasons to put the extraction shaft in the middle of the tunnel tube, so that expensive alternatives remain the only solution, such as transverse ventilation, semi-transverse ventilation or a separate air extraction tunnel, which opens into the middle of the tunnel tube.

The design of an extraction shaft or preferably the shaft tower is often a compromise between functionalism and aesthetic design. The polluted air must, however, be blown out above the local turbulance around among other things buildings to prevent the pollution of the air in the immediate surroundings of the tunnel. In addition it must be borne in mind that if the air capacity of the extraction shaft is reduced according to need (for example to 50%), the diluting effect due to the induction effect also decreases and the polluted column of air stays at a much lower level.

In designing a road tunnel in Baden Baden, (Germany), a polluted air shaft was chosen with an outflow rate of 25 m/s. By installing an adjustable outflow nozzle the outflow rate is held at a constant 25 m/s also if the air capacity of the extraction shaft is reduced to approx. 35% of the maximum capacity. In Japan, where the percentage of diesel vehicles is very high, static electrofilters have been fitted which filter the polluted air before it is blown out into the atmosphere. Such an electrofilter can, however, only separate out a certain part of the polluted air such as soot particles, abrasion particles from rubber tyres and dust blown into the air. A reduction of the gaseous pollution is not achieved with this method so that CO and NO, concentrations are not reduced. The removal or filtering of these gaseous pollutants in the relatively low concentrations which occur in the polluted air of road tunnels involves extremely high investments due to the large volumes of air involved. Such processes are therefore inefficient and not yet feasible economically.

The maximum volume of air in the various polluted air extraction shafts in use in Switzerland varies from 275 to 390 m^3 /s per tunnel tube with two traffic lanes in 1 direction. This indicates that very large volumes of air are in deed involved which are blown out through the extraction ventilators and the polluted air shaft.

14.3 NOISE POLLUTION INSIDE THE TUN-NEL

20 to 25 years ago a maximum noise level of 75 to 80 dB(A) was employed in a road tunnel. This low value was considered necessary in the event of accidents in the tunnel to be able to give instructions to motorists through the loudspeaker system. In addition to large sound absorbers near the ventilators the whole of the ceiling in the tunnel is covered by a sound absorbing material.

Due to changing opinions about the transport of dangerous substances and the subsequent increased risk of fire in the tunnel, it is necessary to protect the ceiling of the tunnel with a fire-resistant coating. This coating has only a very small sound absorbing effect with the result that the noise level in the tunnel is higher than in the past. The noise created by the traffic is absorbed less. In such a tunnel a large goods vehicle on accelerating produces a sound intensity of 90 to 100 dB(A).

Instructions are currently not only given through a loudspeaker system but also by means of a special aerial placed in the tunnel. If the car radio is tuned to the FM reception of radio 1, 2 or 3 the message can be received in this way. The transmission from Hilversum is interrupted by the instructions from the control room of the tunnel.

A low sound intensity level in the road tunnel is less important due to this change in the communication system. It is clear that the design of the ventilation system could be somewhat louder. A sound intensity resulting from the ventilation system of approx. 90 dB(A) is in fact permitted in a lot of countries in Europe. The A-corrected total sound intensity is an unfortunate choice because the A-correction can only be applied up to approx. 65 dB(A). The NR 85 value according to the old ISO standard [1] approximately matches 90 dB(A). NR 85 is also employed in a lot of countries for the permissible sound intensity in road tunnels resulting from the ventilation system.

14.4 NOISE POLLUTION OUTSIDE THE TUN-NEL

Noise pollution outside the tunnel primarily involves hindrance due to noise which arises as a result of traffic and the noise production from the ventilation system which is running. Completely different requirements apply to noise pollution outside the tunnel compared to those inside the tunnel. The following acceptable noise levels are applicable in the Netherlands which relate to the habitation of plots of land situated near the tunnel. The sound levels by the nearest house may not be higher at night than 40 dB(A) and during the day than 50 dB(A). It is therefore irrelevant if this source of sound comes from inside or outside the tunnel. Or in other words: in the case of the nearest situated house a sound intensity of no higher than 50 dB(A) may occur during the day and no higher than 40 dB(A)during the night with all the ventilators working at full capacity. This requirement only applies, however, if the system causing the noise pollution is regularly in operation for a long time. For incidental cases the higher permissible sound intensities apply. The reader is referred to [2] for more information.

The sound intensity level can be reduced by the ventilation design and by using sound absorbers. The effect of traffic noise is a separate subject which is not dealt with here. See [3] for information on this

subject.

14.5 SAFETY MEASURES AND PROCEDURES

The ventilation system of a tunnel is used during disasters to limit the consequences of these disasters. Depending on the type of ventilation system installed more or less than adequate measures can be taken. Since only longitudinal ventilation by means of boosters, whether or not combined with an open injector, is important for the future, attention is only given to this type of ventilation. The underlying ideas can, however, be applied to other ventilation systems which still occur in older tunnels.

Longitudinal ventilation in combination with twoway traffic is very strongly advised against. This is certainly very important for tunnels in which the transport of dangerous substances is permitted because the consequences of a disaster are always much more serious and more difficult to control. From the safety point of view two-way traffic in tunnels with longitudinal ventilation is only permitted in exceptional circumstances. The increased risk only occurs for a short time therefore the chance of a dangerous situation remains small.

A distinction can be made between an accident in which dangerous substances are involved and an accident in which this is not the case. Since all the national road tunnels in the Netherlands will in the future be suitable for the transport of dangerous substances, only accidents in which dangerous substances are involved are dealt with. Furthermore the approach depends on whether or not fire breaks out. A few indications are given, without striving to be exhaustive, to help the people involved in the disaster who are responsible for dealing with it.

14.5.1 Installed safety measures

Because the boosters in the tunnel are fixed they are exposed to high temperatures and corrosive fumes in the event of fire. From considerations concerning safety and efficiency the boosters are therefore distributed over the length of the tunnel. It is sometimes possible to fix the boosters in groups next to each other on the ceiling. In other cases the boosters are installed distributed over the length of the tunnel and on one or both sides of the cross section. The temperature resistance of the boosters must be at least 250 to 300°C and must be withstood for 1 hour. Above this level the boosters may stop working and then they must be replaced or overhauled.

It is evident that the temperature at the boosters very much depends on the size of the fire, the distance to the source of the fire and the volume of ventilated air. In the case of small fires the temperature of the fumes can be lowered by working with a large surplus of air. In the case of fires in the worst scenario it is not possible to reduce the temperature to some extent with a "normal-sized" ventilation system: the volumes of air required are many times larger than can be supplied by the ventilation system. The distribution of the boosters has on the one hand the aim of compensating the resistance of the tunnel and on the other hand the aim in the event of fire of not losing all the boosters simultaneously because of high temperatures. In addition it must be borne in mind that an asymmetrical distribution in which more boosters are installed at the beginning of the tunnel is better in the event of fire. For more information see Chapter 5, section 5.6.4. "Longitudinal ventilation".

Another safety measure is the reversibility of the boosters. To limit damage as much as possible the situations when the system must be reversed are described in Chapter 2, section 2.5.8. Chapter 5, section 5.6.5 also provides information about the reversal of the ventilation direction.

A switch in the control system ensures that the ventilation systems in both tunnel tubes are switched on in the event of fire so that they continue to work in the same direction to prevent an aerodynamic short circuit. This switch also ensures that this ventilation direction is chosen in the first instance whereby the tunnel tube is ventilated downstream from the site of the disaster in the direction of the exit opening. The capacity of the ventilation system in both tunnel tubes must be adjusted independently of each other and in such a way that the air speed in the "clean" tunnel tube is always lower than in the tube where the fire is raging.

The probability of an accident depends on whether or not there is a traffic monitoring system. A socalled AID (Automatic Incident Detection) system is always installed on a motorway with a specific traffic intensity, while a supplementary SOS System (Going-Below-the-Speed System) is installed in a tunnel. This system, which has the purpose of limiting or preventing the number of head-to-tail collisions makes a desirable contribution to warning the control room in time. By filtering the traffic early by means of having the traffic regulating system before the tunnel tube it is possible to prevent this situation from occurring in the majority of cases. Due to the fact that the SOS system also gives a warning in the "quiet" hours if a vehicle is travels into the tunnel below a set speed, measures can be taken by the control room on time.

Traffic lights in front of the tunnel make it possible to allow the traffic to stop in time so that in the event of a disaster in the tunnel tube as few as possible motorists are exposed to the danger.

The CCTV system functions as the "eyes" of the control room. This system is activated automatically by signals from the AID system, the SOS system, the various door switches and the reports of height or is activated manually by the control room. This supplies the most important information on the basis of which the correct measures can be taken with respect to the ventilation system.

The "ears" of the control room are the telephone, the intercom and the radiotelephone. Intercom sets are installed in the tunnel at the powder extinguisher points and aid stations. In addition a radiotelephone connection can be made between the control room and the emergency service personnel working in the tunnel by installing a special aerial in the tunnel.

To prevent unauthorized people driving into the tunnel during a traffic jam a mobile barrier is provided just after the traffic lights. This mobile barrier is also called VEVA or LUKUVA and has two purposes, namely opening the so-called central reservation passage and the simultaneous closure of the blocked tunnel tube. By opening the central reservation passage it is possible to use the other tunnel tube in the opposite direction so that the traffic can be allowed to continue in the event of a traffic jam. The emergency service personnel can also use this route in the event of a disaster. In the normal operating situation the barrier is placed in the central reservation and forms a unit with the crash barrier there. This is extremely advisable from the safety point of view.

In the event of a disaster the escape corridor serves as a route by which to leave the tunnel as quickly as possible. It is therefore extremely important for the public as well as for the emergency service personnel that the doors to the escape corridor are provided with clear signs. It is possible from the control room to direct the emergency service personnel to the correct place by means of the closed video system and a radiotelephone connection. The escape corridor is sometimes combined with the ventilation duct which is in between both tunnel tubes. If this duct is to be used as an escape route, then it cannot serve as a ventilation duct at the same time.

The escape route must be at the same level as the surface of the road in the tunnel tube to make it easily accessible to the public. To keep the escape route free of dangerous substances during a fire or disaster this route must be brought under a small overpressure. In addition bad visibility due to the heavy production of smoke must be taken into account when installing the signs for the doors to the escape route. As long as the smoke is not stratified, visibility is best close to the road surface.

A fire detection system in the tunnel tubes only has any point if no other monitoring systems have been installed. Since a tunnel fire is in most cases the result of an accident the traffic monitoring system will have already reported this. The CCTV system provides the control room with the information if in the event of an accident fire has broken out. For the above-mentioned reasons a fire detection system is not installed in tunnel tubes in which other monitoring systems have been installed.

14.5.2 Procedure during disasters and/or fire

Irrespective of the tunnel ventilation system the control room must always take the following measures in the event of fire.

If the control room detects a fire in the tunnel tube, all the traffic is blocked therefore also in the adjacent tunnel tube. This blockage is necessary to give easy access to the site of the fire for the emergency services. The fire brigade can approach the source of the fire down the free tunnel tube from two sides through doors in the central duct to get as close as possible to the source of the fire. The emergency service can also get to the site of the accident quickly because the emergency service vehicles can get as close as possible to the site of the accident down the empty tunnel tube. After reconnaissance by a fireman wearing a compressed air mask and after a report has been made to the commanding officer the emergency assistance work can begin.

The measures taken in the event of a fire have already been discussed in 5.6 so the reader is referred to that section. Several special aspects are explained below. Aerodynamic short circuiting must be taken into account when the tunnel is being ventilated during disasters. This phenomenon, which is particularly important in tunnels with longitudinal ventilation, ensures that part of the tunnel air flowing outside through the exit opening is sucked in again through the entrance opening of the other tunnel tube. The volume of air which is sucked in this way can be as much as 30 to 40%. The prevailing wind direction and the orientation of the tunnel are factors which determine the extent of the aerodynamic short circuit. A so-called smoke wall is often used in the design to limit this phenomenon.

In the event of a disaster it is necessary that the dangerous substances do not penetrate into the tunnel tube from where the emergency assistance is organized. To prevent this from happening the ventilation system should be reversible so that the ventilation direction can be made the same for both tunnel tubes. This means that if it is decided to reverse the direction of the ventilation in the tunnel in which the disaster has occurred, the direction must also be reversed in the other tube.

So as not to expose the motorists to an unnecessary danger in the event of a disaster the traffic is always blocked in both tunnel tubes. Only after the control room has an idea of the nature and extent of the accident is it decided to remove the blockage. One of the first measures which must be taken is switching on the ventilation system in both tunnel tubes, the direction of which is determined in the first instance by the tunnel tube in which the accident takes place. A flow of air should always be created over the site of the accident to prevent dangerous substances and hot gases from flowing in the direction of the stranded traffic. The ventilation system should be provided with a preferred direction so that it is always started in this direction. By connecting the ventilation systems via the control system ensures that the adjacent tunnel tubes are always ventilated in the same direction.

After the control room has switched on the ventilation system the capacity of the ventilation system must be regulated. The control system has an air speed meter and a direction meter in each tunnel tube. On the basis of the values measured in the tunnel more or less ventilators are automatically switched on or off. It may also be necessary to intervene manually to meet the requirements of the fire brigade. The values which must be adjusted depending on the given situation are indicated in Chapter 2, section 2.5.

It has been agreed with the fire brigade that the commanding officer is responsible for dealing with the disaster. The commanding officer has a better idea of the actual situation based on his own observations or those of the firemen in his command. Adaptation of the set ventilation procedure can be necessary. The commanding officer can do this in consultation with the control room. It is possible for the control room to have radiotelephonic contact with the commanding officer. To give the fire brigade the opportunity to adapt the chosen ventilation procedure in urgent cases without the intervention of the control room a limited control device is available near the entrance of each tunnel tube.

APPENDIX A

Relationship between the CO concentrations of inhaled air and the build up of Hb-CO in the blood with respect to time and activity (according to May). BLJLAGE A



Time (hours/minutes)

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APPENDIX B1

Coefficient of wall friction λ as a function of Reynolds number and the relative wall roughness δ /Dh (according to Moody).

 $\frac{\delta}{D_{h}}$

BIJLAGE B1





APPENDIX B2

Nomograph for the coefficient of wall friction in the Re independent area (values for concrete and cement ducts). $\Delta p = \lambda x \frac{L}{D} x \frac{1}{2} x \rho x u_t^2$

$$p = \lambda x \frac{D}{D_h} x \frac{1}{2} x \rho x$$

Source: J. Ackeret et al., Die Luftung der Autotunnel, p. 105.

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Moody, Kirschner

APPENDIX C Probability distribution of the wind

The probability distribution of the wind which is used is based on the wind distribution at the Schiphol metereological station as is given in [3]. The wind is divided into 12 compass points given in degrees and 29 wind speed ranges.

distributive frequency distribution of average hourly potential wind speed (per 100,000 observations)

Schiphol(240)		1951 un	til 1976		whole y	ear	and a subscription of the	open si	te			na a financia a successione de la companya de la co
Classes (m/s)	North 330	360	030	East 060	090	120	South 150	180	210	West 240	270	300
0.0 until 0.9	133.0	143.0	96.0	80.0	107.0	95.0	117.0	164.0	135.0	161.0	145.0	94.0
1.0 until 1.9	441.0	547.0	388.0	432.0	494.0	508.0	581.0	717.0	529.0	655.0	508.0	383.0
2.0 until 2.9	790.0	1018.0	593.0	815.0	984.0	802.0	974.0	1320.0	1106.0	1192.0	841.0	684.0
3.0 until 3.9	938.0	1065.0	882.0	1182.0	1333.0	942.0	1182.0	1547.0	1599.0	1253.0	1063.0	836.0
4.0 until 4.9	870.0	870.0	856.0	1317.0	1356.0	864.0	1241.0	1501.0	1701.0	1132.0	1101.0	770.0
5.0 until 5.9	762.0	709.0	820.0	1100.0	1009.0	550.0	860.0	1207.0	1566.0	1126.0	1119.0	742.0
6.0 until 6.9	764,0	659.0	738.0	1115.0	820.0	455.0	705.0	1000.0	1435.0	1189.0	1087.0	730.0
7.0 until 7.9	624.0	415.0	455.0	879.0	519.0	219.0	470.0	728.0	1131.0	1226.0	979.0	575.0
8.0 until 8.9	369.0	263.0	384.0	589.0	293.0	78.0	266.0	517.0	921.0	896.0	772.0	482.0
9.0 until 9.9	286.0	150.0	214.0	443.0	173.0	48.0	172.0	318.0	677.0	839.0	584.0	400.0
10.0 until 10.9	172.0	74.0	134.0	292.0	136.0	29.0	96.0	212.0	524.0	699.0	453.0	299.0
11.0 until 11.9	98.0	44.0	78.0	136.0	57.0	11.0	38.0	130.0	319.0	525.0	315.0	192.0
12.0 until 12.9	72.0	29.0	36.0	75.0	33.0	3.9	22.0	75.0	251.0	452.0	260.0	144.0
13.0 until 13.9	42.0	19.0	13.0	29.0	12.0	0.9	11.0	37.0	146.0	301.0	173.0	74.0
14.0 until 14.9	28.0	4.8	7.0	15.0	5.7	2.2	2.2	14.0	82.0	203.0	90.0	43.0
15.0 until 15.9	13.0	2.2	2.6	11.0	3.1	1.8	0.4	7.5	56.0	115.0	60.0	25.0
16.0 until 16.9	8.8	1.8	2.2	3.1	0.9	0.0	0.9	1.8	29.0	79.0	40.0	27.0
17.0 until 17.9	4.8	0.9	0.0	1.3	1.3	0.0	0.0	4.8	21.0	83.0	38.0	17.0
18.0 until 18.9	2.6	0.9	0.0	0.0	1.3	0.0	0.0	3.5	17.0	50.0	27.0	13.0
19.0 until 19.9	1.8	0.9	0.0	0.0	0.0	0.0	0.0	0.9	7.5	17.0	14.0	7.5
20.0 until 20.9	1.3	0.0	0.0	0.0	0.0	0.0	0.0	0.4	1.3	15.0	7.9	2.6
21.0 until 21.9	1.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	5.3	7.0	3.1
22.0 until 22.9	0.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	9.2	1.3	2.2
23.0 until 23.9	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.9	2.2	1.8	0.4
24.0 until 24.9	1.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	1.8	0.9	0.9
25.0 until 25.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.0	1.3
26.0 until 26.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	2.2
27.0 until 27.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
28.0 and more	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
totals	6427	6017	5699	8515	7339	4609	6737	9506	12255	12226	9689	6550

APPENDIX D Determination of the pressure coefficient curve from the NLR measurement results

1 GENERAL

The determination of the pressure coefficient is based on the Schiphol tunnel. This is not based on the actual measurement results but on adaptations of these measurement.

The Schiphol tunnel cannot be considered representative of the tunnels in the Netherlands because of its extensive light-reflecting grid constructions.

To give the measurement results of the model research carried out for the Schiphol tunnel a more general application only the wind pressures on the exits of the Schiphol tunnel are used. These have been attributed to an imaginary tunnel tube lying north-south with the entrance (in fact the exit of the western tube of the Schiphol tunnel) on the southern side and the exit (in fact the exit of the eastern tunnel tube) on the northern side.

The measurement results of the exit of the western tube are much more regular than those of the eastern tube, which is more affected by environmental factors.

To be able to discount these environmental factors the schematization is based on the western tube.

The schematization distinguishes 4 situations:

- 1. Entrance with positive direction of ventilation $(u_t > 0)$
- 2. Entrance with negative direction of ventilation $(u_t < 0)$
- 3. Exit with positive direction of ventilation $(u_t > 0)$
- 4. Exit with positive direction of ventilation $(u_t < 0)$

These cases are strongly related to each other in pairs, since the entrance as well as the exit is based on the eastern tube of the Schiphol tunnel.

This has resulted in 4 procedures in the program:

ENTRANCE POSITIVE ENTRANCE NEGATIVE EXIT POSITIVE EXIT NEGATIVE

The wind resistance R_{wind} is given by the realtionship:

$R_{wind} = 0.5 \times \rho \times u_w^2 \times C_{wind} \times$	(1) (1)	
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In general the pressure coefficient C_{wind} can be described by the following relationship:

 $C_{wind} (\beta) = A x \cos^2 \beta + B x \cos \beta + C$ (2)

$A = A_{o} + A_{1} \times u_{v}/u_{w}$	(3)
$\mathbf{B} = \mathbf{B}_{\mathbf{o}} + \mathbf{B}_{1} \mathbf{x} \mathbf{u}_{\mathbf{v}} / \mathbf{u}_{\mathbf{w}}$	(4)
$C = C_0 + C_1 \times u_t / u_w$	(5)

 β = wind direction in relation to the axis of the tunnel
The following values should be assigned to the coefficients:

Case	Description	Procedure	A,	A ₁	Во	В1	C,	C1
1	Entrance with $u_i > 0$	ENTRANCE POSITIVE	0,40	-0,28	0,20	0,16	-0,25	0
2	Entrance with $u_i < 0$	ENTRANCE NEGATIVE	0,40	-0,14	0,20	0,35	-0,25	0,21
3	Exit with $_{i} > 0$	EXIT POSITIVE	0,40	0,14	0,20	-0,35	-0,25	-0,21
4	Exit with $i < 0$	EXIT NEGATIVE	0,40	0,28	0,20	-1,06	-0,25	o

Substitution of equations (3) to (5) in equation (2) gives an equation for the wind pressure coefficient as a function of wind direction, wind speed and the (still unknown) Uair.

So for example for ENTRANCE POSITIVE it applies that:

$C_{wind} (\beta) = (-0.28 \cos^2\beta - 1.06 \cos\beta) \times u_t / u_w + 0.4 \cos^2\beta - 0.20 \cos\beta - 0.25$ $= \alpha_{w1_entrance} \times u_t / u_w + \alpha_{w2_entrance}$	(6) (7)
The eventual wind resistance is given by multiplying (6) by	
$0.5 \mathbf{x} \mathbf{\rho} \mathbf{x} \mathbf{u_2}^2 \mathbf{x} \mathbf{A}$	(8)
C _{wind} is given by:	
$C_{wind} = C_{wind1} \times u_t + C_{wind2}$	(9)
with:	
$C_{wind1} = 0.5 \times \rho \times u_w \times \alpha_{w_{entrance}} \times A$	(10)
$C_{wind2} = 0.5 \times \rho \times u_w^2 \times \alpha_{w2_{entrance}} \times A$	(11)

The other 3 procedures are derived in a similar way.









Tunnel element data:				
element	length	gradient	(%)	
1	200.0	-4.5		
2	130.0	0.0		
3	200.0	4.5		

Traffic	data:				
GOODS V	EHICLES				
Description			Percentage		
% goods	vehicles	of	total:	10.0	
% goods	vehicles		HD 1:	33.3	
% goods	vehicles		HD 2:	33.3	
% goods	vehicles		HD 3:	33.4	
Resista	nce coeffi	cient	(-):	1.00	
Flow su	rface area		(m²):	6.50	

Fixed cumer data		
Orientation of entrance openin	g(*):	0.1
Orientation of exit opening	(*):	180.0
CO concentration entrance (ppm):	0.0
Cross section of the elements	(m²):	60.0
Circumference of the elements	(m):	35.8
Number of traffic lanes	:	3

CARS/VANS					
Description	Percentage				
% cars	15-04:	25.0			
% cars	US 83:	25.0			
% cars	Diesel:	25.0			
% vans	15 04:	10.0			
% vans	US 83:	5.0			
% vans	Diesel:	10.0			
Resistance coefficient	(-):	0.55			
Flow surface area	(m ²):	2.00			
File name	:	ZB-EAST			
Name of tunnel	:	Zeeburg eastern tub			
Fh	(-):	0.7			
Fo	(-);	1.0			

Ventilator data:			
	Front of	tunnel	distributed
Number of boosters	(-):	0.0	30,0
Exit speed	(m/s):	40.5	40.5
Exit output flow rate	e (m³/s):	12.5	12.5
Efficiency	(-):	0.75	0.75
Resistance data:			
Inflow resistance	(-):	0.6	
Outflow resistance	(-):	0.6	
Wall friction coeffic	cient(-):	0.025	I.



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