JTG

Recommended Industry Standards of
the People's Republic of China
中华人民共和国行业推荐性标准

JTG/T D70/2-02—2014(EN)

Guidelines for Design of Ventilation of Highway Tunnels

公路隧道通风设计细则

(英文版)

Issued date: July 14, 2014 Effective date: August 1, 2014

Issued by Ministry of Transport of the People's Republic of China

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中华人民共和国交通运输部

公　　告

第 50 号

交通运输部关于发布《公路隧道设计规范　第一册　土建工程》英、法文版等 7 项公路工程行业标准外文版的公告

为促进公路工程行业标准的国际合作与共享，现发布《公路隧道设计规范　第一册　土建工程》英文版[JTG 3370.1—2018（EN）][代替标准号 JTG D70—2004(E)]及法文版[JTG 3370.1—2018(FR)]、《公路隧道设计规范　第二册　交通工程与附属设施》法文版[JTG/T D70/2—2014(FR)]、《公路隧道照明设计细则》英文版[JTG/T D70/2-01—2014(EN)]、《公路隧道通风设计细则》英文版[JTG/T D70/2-02—2014(EN)]、《公路隧道抗震设计规范》英文版[JTG 2232—2019(EN)]、《公路隧道养护技术规范》英文版[JTG H12—2015(EN)]。

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特此公告。

中华人民共和国交通运输部

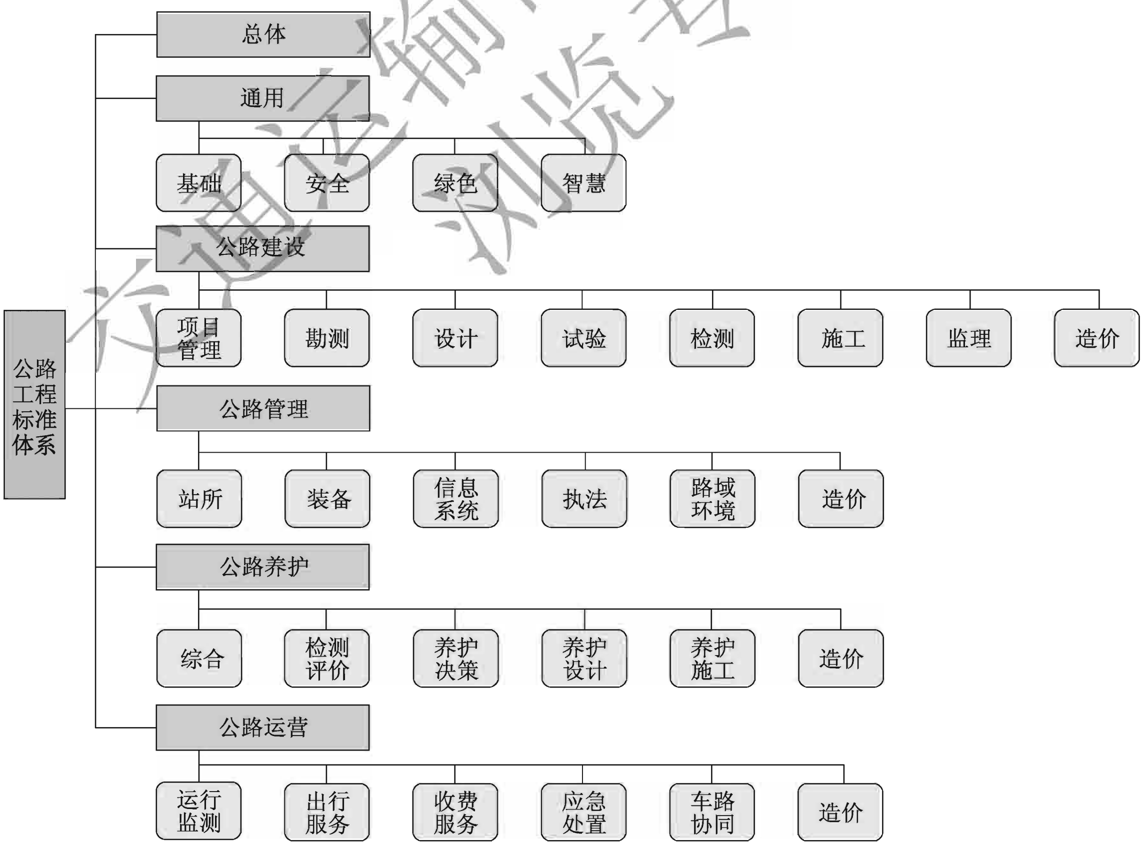
2023 年 9 月 20 日

交通运输部办公厅　　2023 年 9 月 21 日印发

英文版编译说明

标准是人类文明进步的成果，是世界通用的技术语言，促进世界的互联互通。近年来，中国政府大力开展标准化工作，通过标准驱动创新、协调、绿色、开放、共享的共同发展。在丝绸之路经济带与21世纪海上丝绸之路，即“一带一路”倡议的指引下，为适应日益增长的全球交通运输发展的需求，增进世界连接，促进知识传播与经验分享，中华人民共和国交通运输部组织编译并发布了一系列中国公路行业标准外文版。

中华人民共和国交通运输部发布的公路工程行业标准代号为JTG，体系范围涵盖公路工程从规划建设到养护和运营管理全过程所需要的设施、技术、管理与服务标准，也包括相关的安全、环保和经济方面的评价等标准。



《公路隧道通风设计细则》(简称《细则》)是公路隧道通风设计有关的重要技术标准,主要用于各等级的新建和改扩建山岭公路隧道通风设计和运营,可供隧道运营管理企业、设计院、施工企业、工程监理等使用。2000 年由交通部首次发布实施《公路隧道通风照明设计规范》(JTJ 026.1—1999),作为公路隧道通风设计有关的首部专业规范,对保障我国公路隧道运营安全、推进公路隧道通风科技进步和规范设计行为,均起到了重要作用。《细则》在充分总结中国相关科研成果和大量工程经验的基础上,吸收借鉴国际先进的公路隧道通风技术,进行改进与修订,2014 年发布修订版《细则》。《细则》以科学合理、经济安全、利用高效为基本制订原则,重点对公路隧道通风设计的技术要求进行统一和规范,主要内容包括通风计算参数、通风方式、计算方法、火灾防烟与排烟、风道、风机房与通风井、风机选型与布置等。本英文版的编译发布便是希望将中国的工程经验和技术成果与各国同行进行交流分享,为其他国家山岭公路隧道通风设计与通风防灾提供参考借鉴。

《细则》英文版的编译工作由中华人民共和国交通运输部委托招商局重庆交通科研设计院有限公司主持完成,并由中华人民共和国交通运输部公路局组织审定。本规范在编译过程中得到欧美多名专家的支持,特别感谢巴基斯坦专家 Asim Amin、澳大利亚专家 Arnold Dix、中国专家李颖臻,以及巴基斯坦专家 Abu Bakar、Saif Ali Tahir 等在编译与审定期间给予的协助与支持。

本英文版标准的内容与现行中文版一致,如出现异议时,以中文版为准。

感谢中文版主要编写者蒋树屏、陈建忠先生在本英文版编译与审定期间给予的指导与支持。

如在执行过程中发现问题或有任何修改建议,请函告英文版主编单位(地址:重庆市南岸区学府大道 33 号隧道与地下工程研究院,邮政编码:400067,电子邮箱:chengliang@cmhk.com),以便修订时研用。

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The People's Republic of China

Ministry of Transport

Public Notice

No.50

Public Notice on Issuing the English and French Versions of Seven Highway Engineering Industrial Standards including *Specifications for Design of Highway Tunnels Section 1 Civil Engineering*

The English and French versions of *Specifications for Design of Highway Tunnels Section 1 Civil Engineering* [JTG 3370.1—2018 (EN), substituting JTG D70—2004 (E); and JTG 3370.1—2018(FR)], the French version of *Specifications for Design of Highway Tunnels Section 2 Traffic Engineering and Affiliated Facilities* [JTG D70/2—2014(FR)], the English version of *Guidelines for Design of Lighting of Highway Tunnels* [JTG/T D70/2-01—2014(EN)], the English version of *Guidelines for Design of Ventilation of Highway Tunnels* [JTG/T D70/2-02—2014 (EN)], the English version of *Specifications for Seismic Design of Highway Tunnels* [JTG 2232—2019(EN)], and the English version of *Technical Specifications of Maintenance for Highway Tunnel* [JTG H12—2015(EN)] are issued hereby for promoting international cooperation and sharing of standards in highway engineering industry.

The general administration and final interpretation of theforeign language versions of the above mentioned standards belong to Ministry of Transport, while particular interpretation for application and routine administration shall be provided by China Merchants Chongqing Communications Technology Research & Design Institute Co., Ltd.

Inevent of any ambiguity or discrepancies between the foreign language versions and Chinese version, the Chinese version should be referred and accepted.

Comments, suggestions and inquiries are welcome and should be addressed to China Merchants Chongqing Communications Technology Research & Design Institute Co., Ltd. (Address: Institute of Tunnel and Underground Engineering, No. 33 Xuefu Avenue, Nan'an District, Chongqing, P. R. China; Postal Code: 400067; E-mail: chengliang@cmhk.com).

It is hereby announced.

Ministry of Transport of the People's Republic of China

September20, 2023

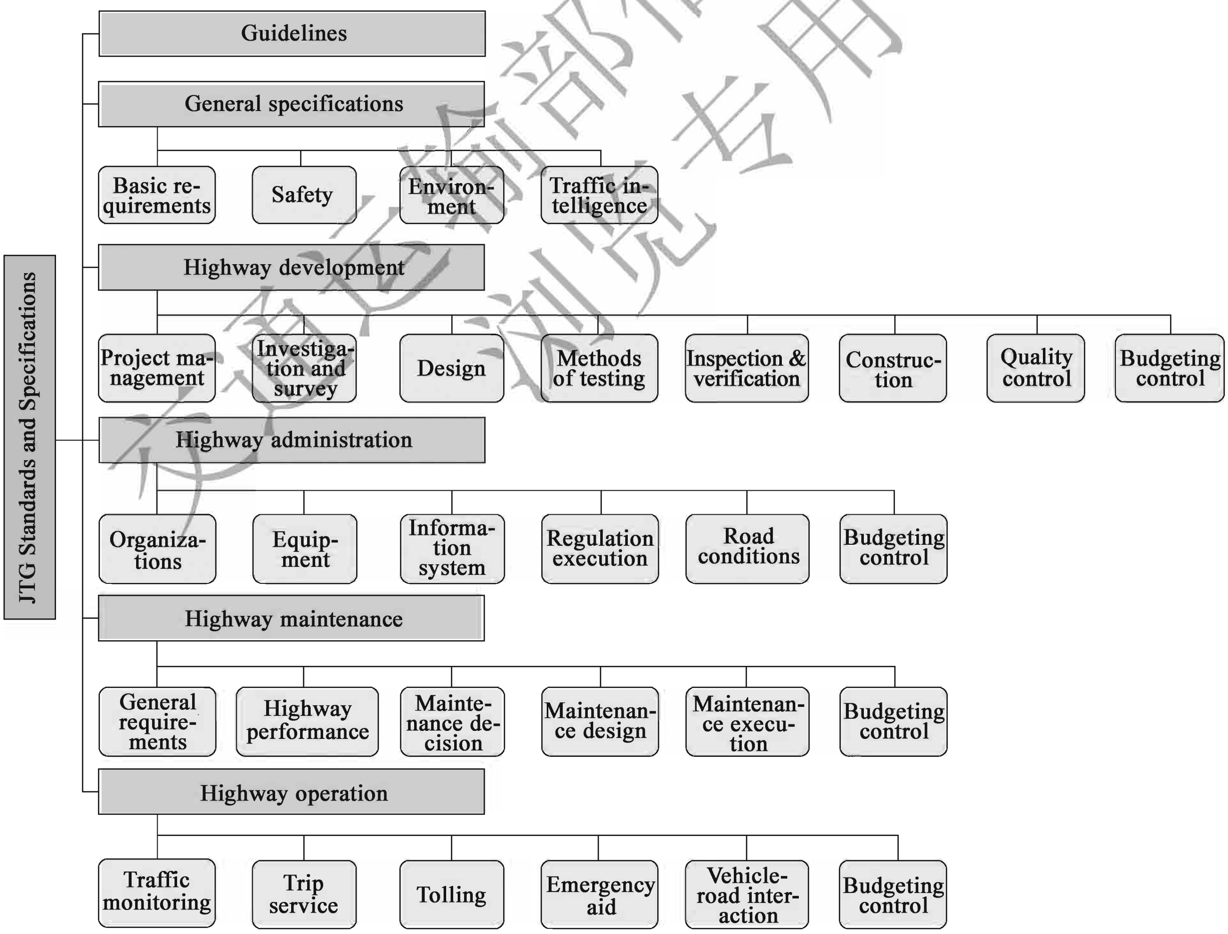
General Office of Ministry of Transport Printed on September 21, 2023

Introduction to English Version

Standards reflect the achievement of civilization and progress, provide common languages for technical communications and improve global connectivity. In recent years, Chinese government has been proactively implementing the standardization to stimulate innovation, coordination, greening and opening up for shared development in China and worldwide. In light of mutual development along the Silk Road Economic Belt and the 21st – Century Maritime Silk Road (so called the "One Belt One Road" initiative), the Ministry of Transport of the People's Republic of China organized translation and published international version of Chinese highway industry standards and specifications to cope with the increasing demands for international cooperation in world transportation, achieve interconnected development and promote knowledge dispersion and experience sharing.

JTG is the designation referring to the standards and specifications of highway transportation industry, issued by the Ministry of Transport of the People's Republic of China. It covers the standards and specifications in terms of facilities, technology, administration and service for whole process from highway planning through to highway maintenance. The criteria for safety, environment and economy assessment are also included.

The*Guidelines for Design of Ventilation of Highway Tunnels* (hereinafter referred to as the *Guidelines*) are important technical standards for the ventilation design of highway tunnels. It is mainly used by tunnel operation management enterprises, design institutes, construction enterprises and engineering supervisors for ventilation design and operation of new, modified and expanded mountain highway tunnels at different levels. In 2000, the *Specifications for Design of Ventilation and Lighting of Highway Tunnel* (JTJ 026. 1—1999) were first issued for implementation by the Ministry of Transport. As the first professional specifications related to the ventilation design of highway tunnels, they have played an important role in ensuring the operation safety of highway tunnels in China, promoting the scientific and technological progress of highway tunnel ventilation and standardizing the design behaviors. On the basis of fully summarizing the relevant scientific research achievements and rich engineering experience of China, the *Guidelines* were improved and revised with reference to international advanced highway tunnel ventilation techniques. In 2014, the revised version of the *Guidelines* was released. Based on the basic principles of scientific rationality, economic safety and high utilization efficiency, the *Guidelines* focus on unifying and standardizing the technical requirements of highway tunnel ventilation design, and involve ventilation calculation parameters, ventilation methods, calculation methods, fire smoke prevention and exhaust, air ducts, ventilator rooms and ventilation shafts, fan selection and layout. The purpose of compiling and publishing this English version is to exchange and share China's engineering experience and technical achievements with counterparts in other countries, and to provide reference for the ventilation design and disaster prevention of mountain highway tunnels in other countries.



The Ministry of Transport of the People's Republic of China entrusted China Merchants Chongqing Communications Technology Research & Design Institute Co., Ltd. to preside over the compilation of the English version of the*Guidelines*, and the Highway Bureau of the Ministry of Transport of the People's Republic of China organized the review. These Specifications were supported by many experts in Europe and America during compilation. Special thanks are also given to Pakistani expert Asim Amin, Australian expert Arnold Dix, Chinese expert Li Yingzhen, Pakistani experts Abu Bakar and Saif Ali Tahir for their assistance and support during the editing and approval of these Specifications.

The English version of this standard is consistent with the current Chinese version. Inthe event of any ambiguity or discrepancies, the Chinese version shall be referred and accepted.

Gratitude is given here to Mr. Jiang Shuping and Mr. Chen Jianzhong, the editors in charge of Chinese version, for their guidance and support during the editing andapproval of the English version.

Comments, suggestions and inquiries are welcome and should be addressed to the editing organization in charge ofthe English version (address: Tunnel and Underground Engineering Research Institute, Merchants Chongqing Communications Technology Research & Design Institute Co., Ltd., No. 33, Xuefu Avenue, Nan'an District, Chongqing, postal code: 400067, e-mail: chengliang@cmhk.com).

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Foreword to Chinese Version

According to the *Notice on* 2007 *Compilation and Revision Plan of Highway Engineering Standard* (JGLF [2007] No. 378) issued by the Ministry of Transport, China Merchants Chongqing Communications Technology Research & Design Institute Co., Ltd. is responsible for the compilation of *Guidelines for Design of Lighting and Ventilation of Highway Tunnels*.

As the first professional standard for the design of ventilation of highway tunnels, the *Specifications for Design of Ventilation and Lighting of Highway Tunnels* (JTJ 026.1—1999) has played an important role in the operation safety safeguard and ventilation technology promotion and design standardization of highway tunnels since its issuance on June 1, 2000. For more than ten years, as the size of highway tunnel enlarged and the types of highway tunnel enriched, we have gained rich experience in the construction, operation and management. Moreover, the technological progress of the automobile industry in reducing pollutants emissions generally and ventilation-related technology and product performance improved. On the basis of engineering practice and new scientific achievements in recent years, the *Guidelines* actively introduces new theories, new technologies and new methods and draws lessons from foreign experience and advanced technologies in the ventilation of highway tunnels. With consideration to the operating ventilation technology development trend of highway tunnels and the status of tunnel construction in China, tunnel ventilation requirements in the *Design Specification for Traffic Engineering of Highway Tunnel* (JTG/T D71—2004) and *Specifications for Design of Ventilation and Lighting of Highway Tunnels* (JTJ 026.1—1999) are amended and expanded and the *Guidelines for Design of Ventilation of Highway Tunnels* (JTG/T D70/2-02—2014) is hereby issued after approval for implementation.

The *Guidelines* consists of twelve chapters and five appendixes: 1 General Provisions, 2 Glossary and Symbols, 3 Ventilation Planning and Survey, 4

Ventilation Mode, 5 Ventilation Standard, 6 Required Air Volume Flow, 7 Ventilation Calculation, 8 Duct, 9 Fan Room and Ventilation Shaft, 10 Smoke Prevention and Extraction in Case of Tunnel Fire, 11 Fan Selection and Layout, 12 Design Principles of Ventilation Control, Appendix A On-way Resistance Coefficient, Appendix B Pressure Loss Coefficient of U-shaped and Z-shaped Ducts, Appendix C Other Pressure Loss Coefficient of Tunnels and Ducts, Appendix D Common Units and Unit Conversion in Fluid Mechanics, and Appendix E Examples of Ventilation Calculation.

Compared with the*Specifications for Design of Ventilation and Lighting of Highway Tunnels*(JTJ 026.1—1999), the ventilation standard, ventilation mode, ventilation calculation parameters and other items are revised and improved, and the ventilation planning and survey, smoke prevention and extraction in case of tunnel fire, duct, fan room and ventilation shaft, fan selection and layout and other items are supplemented and improved too.

All units related shall inform routine management team of the problem and suggestions found in implementation for reference in revision by writing to the contact person Tu Yun at 33 Xuefu Avenue, Nan'an District, 400067, Chongqing Municipality via Tel. No. 023-62653440, Fax No. 023-62653078 and E-mail No. tuyun@cmhk.com.

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Contents

1 General Provisions

1.0.1 These *Guidelines* are intended to implement the national technical and economic policies, unify the ventilation design standards of highway tunnels, guide the highway tunnel ventilation design to conform to the principles of scientific, reasonable, economic, safe and efficient utilization and provide a ventilation technical reference for tunnel operation.

***Background*:**

For more than ten years, asthe construction size of highway tunnels generally enlarged, we gained rich experience in construction and operation of highway tunnels, and made progress in relevant technology. Moreover, the technological progress of automobile industry makes its pollutants emissions generally declined and ventilation-related product performance improved. Therefore, it is necessary to formulate appropriate design standards for ventilation technology progress, automobile industry technology status and others.

1.0.2 These *Guidelines* are applicable to the newly-built and upgraded mountain tunnel of expressway, Class-I, Class-II, Class-III and Class-IV highways.

***Background*:**

The *Guidelines* are prepared for the mountain tunnels of highways at different classes. Other tunnels such as submerged tunnel, urban tunnel and mountain tunnel have no basic difference in ventilation mode, ventilation calculation and other aspects, but their main difference lies in ventilation standards.

1.0.3 Highway tunnel ventilation shall be incorporated into the overall design of a tunnel.

***Background*:**

Tunnel ventilation plays an important role in the overall design ofa tunnel, which is closely related to tunnel length, longitudinal grade and others. The increase of tunnel length and longitudinal grade *will lead to the increase of ventilation system size, operation and maintenance cost. The layout of fan room and ventilation shaft in long and extra-long tunnels is related to the topography and geological conditions of tunnels. An inappropriate site selection will greatly increase the construction cost. As a result, ventilation design shall be incorporated into the overall design, and jointly selected by alignment, structure, geology, ventilation and other professional engineers to minimize the overall cost and risk and reduce the operating costs in future.*

1.0.4 As for the highway tunnel ventilation design, the technological and economic comparison and reasonable ventilation scheme shall be made pursuant to highway class, tunnel length, design speed, design traffic volume, quantity of lanes, vertical and horizontal alignments, topography and geology, tunnel elevation, natural condition of tunnel site and other factors.

1.0.5 The design hourly volume (DHV) in the ventilation of highway tunnel shall be the design peak hourly volume (PHV) of hybrid vehicles.

***Background*:**

Traffic volume and traffic composition are the important basic data for tunnel ventilation design. Pursuant to relevant provisions ofTechnical Standards for Highway Engineering (JTG B01), the adaptive traffic volume of highways is the annual average daily traffic (AADT) of passenger car unit (PCU) converted from that of various vehicles, whose unit is pcu/d. The design (forecasted) traffic volume of highways proposed in the feasibility study report is also the AADT of PCU converted from that of various vehicles. But for the same kind of vehicles, the pollutants emissions of gasoline vehicles or diesel vehicles is different; and for the vehicles with the same kind of engine, the pollutants emissions of heavy vehicles, large vehicles and small vehicles is different too. Therefore, even if the AADT (pcu/d) of PCU is the same, their traffic composition is different, and the total pollutants emissions are different too. Meanwhile, the distribution of the traffic volume in the tunnel in daily operation within 24 hours is uneven. Therefore, in ventilation design, it is necessary to convert the traffic volume of PCU into the design PHV of hybrid vehicles in accordance with "Representative Vehicle Types and Vehicle Conversion Coefficient" and traffic composition of design items in Technical Standards for Highway Engineering (JTG B01).

1.0.6 Ventilation design of highway tunnel shall be based on normal traffic conditions and such abnormal traffic conditions as fire and congested traffic respectively.

***Background*:**

Asa highway tunnel is a closed driving environment, it is difficult for rescue and safe evacuation. In the case of a fire in the tunnel, the ventilation system is needed to control the flow of smoke to ensure rescue and safe evacuation. Therefore, the ventilation facilities equipped in the ventilation system shall meet the requirements of disaster prevention and smoke extraction in addition to *operating requirements of normal traffic conditions.*

Abnormal traffic conditions include not only sudden fire and congested traffic condition, but also the operation, maintenance, repairing, overhauling, construction and other conditions requiring ventilation.

1.0.7 Ventilation design of highway tunnels shall be in accordance with the principles of comprehensive planning and integrated design; and ventilation facilities may be implemented in stages according to forecast traffic volume changes.

***Background*:**
The staged implementation of tunnel ventilation is to save initial investment and realize energy-conservation operation on the premise of safety assurance. When there is a big difference between the short-term and long-term traffic volumes and in the size of short-term and long-term ventilation facilities, if integrated design of ventilation facilities is done in accordance with the long-term size, the initial investment will increase, part of the ventilation facilities will be idle for a long time, and the short-term maintenance cost will increase. At the same time, facilities that have been idled for a long time may be difficult to put into use in future, and result in waste. Therefore, the integrated design and staged implementation of ventilation system may be done according to the short-term and long-term traffic volume forecast.

Generally, the ventilation system may be implemented in two stages according to the short-term and long-term traffic volumes. According to relevant provisions of the Technical Standards for Highway Engineering (JTG B01), the ventilation design stages of expressways and Class-I arterial highway tunnels may be done every 10 years, Class-I highway, and Class-II and Class-III collector-distributor highway tunnels may be done every 7 years, and Class-IV highways may be based on the actual situation.

1.0.8 When the tunnel portal or ventilation shaft opening has environmental protection requirements, the pollutants emissions should be controlled to meet the applicable external relevant provisions of environmental protection.

***Background*:**
Only relevant ventilation standards for the operating environment inthe tunnel are proposed, and no air quality standard outside the tunnel is taken into consideration herein. If the tunnel passes through environmentally sensitive areas and pollutant emissions from the tunnel may affect air quality nearby, the concentration and diffusion range of pollutants shall comply with local environmental protection regulations; and the following corresponding measures shall be taken if necessary:

(*1*) The polluted air in tunnel maybe centrally discharged into the upper air;

(*2*) The concentration ofpollutants emissions in tunnel may be reduced by increasing the ventilation volume; and

(*3*) Pollutants may be purified by electrostatic dust collector, soil-based biofilter system or others.

1.0.9 For ventilation design of highway tunnels, the ventilation facilities' operation scheme shall be determined for differing traffic and operating conditions.

***Background*:**
Tunnel ventilation facilities are provided to meetthe worst case scenario, and the operation of ventilation facilities regardless of working conditions will inevitably increase energy consumption or cause potential safety hazards. The operation scheme of tunnel ventilation facilities is closely related to the traffic volume and traffic condition (fluid traffic condition, congested traffic condition, fire, maintenance, repair, etc.); and there are differences in the traffic volume and traffic condition at different time periods of a day, or different months or seasons of a year. The Guideline is intended to provide a reference for the design and operation management of risk control systems for tunnels.

1.0.10 New theories, technologies, materials and equipment (four "new" ones) shall be actively adopted for the design of highway tunnel ventilation.

***Background*:**
Ventilation facilities of highway tunnels usually are of large power and high energy consumption. Actively adopting the said "four new" ones can improve ventilation efficiency and quality, and save investment and operating costs.

1.0.11 In addition to the *Guidelines*, highway tunnel ventilation design shall also comply with relevant existing provisions of the state and the industry.

2 Terms and Symbols

2.1 Terms

2.1.1 Design carbon monoxide concentration

The volume of carbon monoxide (CO) in the polluted air per unit tunnel volume, which is calculated with volume concentration.

2.1.2 Design concentration of particulate matters

The degree of polluted air caused by particulate matters, which is determined by measuring the transmittance of light through particulate matters at a distance of 100m in polluted air, an indicator of visibility in tunnel and also known as extinction coefficient.

2.1.3 Required air volume flow

The amount of required fresh air calculated pursuant to the tunnel conditions based on the environmental index to ensure the safe operation of the tunnel.

2.1.4 Design air volume flow

The air volume flow achieved after fan configuration based on the calculated required air volume flow for the tunnel and meeting operational requirements.

2.1.5 Design air velocity

The axial flow velocity of air in tunnel calculated according to the design air volume flow Q_r.

2.1.6 Air pressure

This includes static pressure, dynamic pressure and total pressure. Static pressure is the equal air pressure acting in all directions; dynamic pressure is the pressure produced when air moves at a certain speed; and total pressure is the sum of static pressure and dynamic pressure at any measuring point. The static pressure and total pressure mentioned herein refer to the relative static pressure and relative total pressure of the tunnel or fan.

2.1.7 Longitudinal ventilation

Ventilation flow along the axis (longitudinal direction) of the tunnel in driving space.

2.1.8 Semi-transverse ventilation

The ventilation flow enters (or discharges) along the direction perpendicular to the tunnel axis (transverse direction) or discharges (or enters) along the direction of tunnel axis (longitudinal direction) in the driving space.

2.1.9 Full transverse ventilation

The flow along the direction perpendicular to the axis (transverse direction) in driving space.

2.1.10 Ventilation shaft

The vertical shaft, inclined shaft and parallel pilot tunnel designed for the ventilation of highway tunnel in operation.

2.2 Symbols

A_r—tunnel clearance area;

D_r—hydraulic diameter of tunnel cross section;

f_a—vehicle condition factor;

f_h—altitude factor;

f_{iv}—longitudinal grade-vehicle speed factor;

f_m—vehicle type factor;

H—tunnel clearance height;

K—designconcentration of particulate matters;

L—tunnel length;

N—design hourly volume (DHV);

n_c—number of vehicles in tunnel (veh.);

n_D—number of diesel vehicle types;

n_+—number of vehicles in tunnel in the same direction as design air velocity v_r;

n_-—number of vehicles in tunnel in the opposite direction to design air velocity v_r;

p—atmospheric pressure attunnel site;

p_0—normal atmospheric pressure;

p_1—atmospheric pressure in fan environment;

Δp—pressure required by ventilation system;

Δp_b—pressure rise at air inlet;

Δp_d—duct ventilation resistance;
Δp_e—pressure rise at air outlet;
Δp_m—natural ventilation effect;
Δp_j—pressure rise of jet fan;
Δp_r—tunnel ventilation resistance;
Δp_t—piston effect of traffic;
Δp_{λ}—tunnelresistance;
$\Delta p_{\zeta i}$—local resistance in tunnel;
Q_{co}—CO emissions in tunnel;
Q_e—exhaust air volume flow;
Q_r—design air volume flow of tunnel;
Q_{req}—required air volume flow of tunnel;
$Q_{req(CO)}$—required air volume flow for diluting CO in tunnel;
$Q_{req(VI)}$—required air volume flow for diluting particulate matters in tunnel;
$Q_{req(f)}$—required air volume flow for smoke extraction in case of fire;
$Q_{req(ac)}$—required air volume flow for tunnel ventilation;
Q_s—design air volume flow of short duct;
Q_{VI}—particulate matter emissions in tunnel;
q_{co}—ERCObasic emission;
q_{VI}—particulate matterbasic emission;
r_l—ratio of large vehicles;
r_d—ratio of diesel vehicles;
S_{kw}—total-pressure input power of axial fan;
S_{th}—total-pressure output power of axial fan;
v_c—critical velocity;
v_n—natural air velocity in tunnel;
v_r—design air velocity in tunnel;
v_t—design speed;
v_{ac}—air velocity for tunnel ventilation.

3 Ventilation Planning and Survey

3.1 Ventilation planning

3.1.1 Highway tunnel ventilation shall be comprehensively designed in combination with alignment plane, longitudinal section, tunnel section form, project stage construction, disaster prevention and rescue and operation management.

***Background*:**

The setting of alignment longitudinal section will affect the size of required air volume flow in tunnel and the setting size of ventilation system, especially for long tunnels that need to set ventilation shafts. The topography, geomorphology and geology of alignment plane position will affect the rationality of ventilation system setting. Therefore, the planning of tunnel ventilation shall cover the form of alignment plane and longitudinal section.

For the tunnel built in stages, the overall ventilation planning of the transformation from single-tubebi-directional traffic to double-tube uni-directional traffic shall be made in combination with the change of traffic volume and the adjustment of mode of transport.

Tunnel operation and management mode, disaster prevention and rescue plan are closely related to the selection ofthe ventilation plan. Therefore, it is necessary to take into consideration these modes and plans at the ventilation design stage.

The ventilation design shall be carried out as per the overall planning of project construction to ensure the rationality of ventilation system size.

3.1.2 Ventilation design of highway tunnels shall follow the following steps:

1 Collectdetails of the highway plane and longitudinal section, where the tunnel is located at

as well as the alignment data of the tunnel such as topography, topographic features and geology.

2 Collect technical data such as highway class, tunnel section, traffic volume, meteorological and environmental conditions of the area where the tunnel is located at, and environmental protection requirements of thetunnel site area.

3 Make the preliminary calculation of tunnel required air volume flow and ventilation scheme comparison according to the collected data; and re-demonstrate the alignment scheme, tunnel length and longitudinal grade when all ventilation schemes fail to meet the requirements of operation safety, economy and environmental protection due to the alignment scheme.

4 Calculate the required air volume flow and determine the design air volume flow according to the ventilation scheme determined by comparison; and calculate the ventilation system resistance in detail.

5 Make fan selection and configuration pursuant to the fan's air pressure, air volume flow and power calculated according to the detailed calculation of ventilation system resistance.

6 Check whether the ventilation system meets the tunnel operation requirements according to the tunnel structure construction and ventilation facilities' parameter changes before the installation ofthe ventilation facilities.

Background:
The general work flow of ventilation design is shown in Figure 3-1. The steps are interrelated; and the results of a step should be fed back into the previous analysis if necessary.

The ventilation scheme comparison and selection's demonstrationis mainly aimed at factors such as ventilation mode, ventilation shaft position, disaster prevention and rescue, construction organization, influence of ventilation system on surrounding environment, and project cost. The rationality, economy and environmental protection of the ventilation scheme are important factors in the selection of tunnel alignment scheme.

The ventilation system's resistance calculation includes natural ventilation effect, piston effect of traffic, fire-induced thermal pressure and tunnel resistance loss. The ventilation scheme also includes the design of the relevant duct and fan room as well as the control mode of fan.

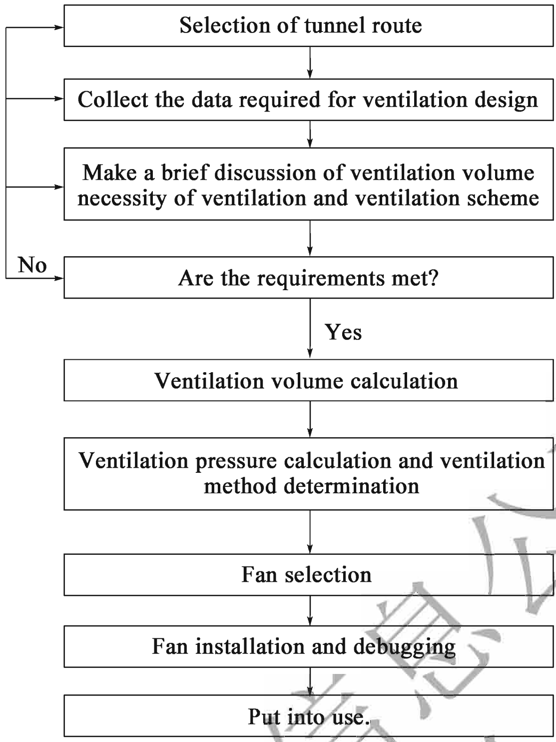


Figure 3-1 Implementation process of ventilation design

Ventilation design and alignment, tunnel structure design and construction are interrelated and interactive. Local changes often occur in the construction process of related tunnel structure. For instance, the tunnel with ventilation shaft for segmental ventilation, the length of duct and ventilation shaft, and connection mode may be changed. In addition, for the fan with different brands but the same model, its performance parameters are slightly different, and the specific installation method or parameters are also different. Therefore, before the fan is installed, it is necessary to check whether the ventilation system meets the requirements according to the tunnel structure changes and the actual equipment used.

3.1.3 The design of the staged implementation of the ventilation system of highway tunnels shall follow the following principles:

1 Make comprehensive consideration according to the traffic volume growth of the segment where the tunnel is located at, the change of thebasic emission of automobile pollutants, the change of the standard of ventilation inside the tunnel built in stages and the standard of environmental air quality outside the tunnel built in stages, the difficulty degree of the staged implementation of tunnel structure and ventilation facilities, and other factors.

2 The equipment installed in each stage shall meet the requirements for disaster prevention and ventilation of tunnels.

***Background*:**

1 Under normal traffic conditions, the ventilation ofa tunnel is mainly to dilute the tailpipe emissions pollutants caused by motor vehicles. With the progress of automobile technology and the improvement of emissions regulations, the emissions of pollutants from motor vehicles in China has been greatly reduced. When the implementation of a new vehicle exhaust emissions limit standard is applied, the emissions of pollutants per vehicle will be reduced, and the necessary size of the ventilation system will also change. Therefore, the basic emission of automobile pollutants is one of the factors affecting the implementation of the ventilation system in stages.

With the development of technology and economy, the air quality inside and outside the tunnel has been improved too. Take the design concentration of CO ina tunnel to be diluted as an example, the Technical Committee of Highway Tunnel Operation of PIARC recommended in Technical Report 1995 that the design concentration of CO shall be $100cm^3/m^3$ when the normal peak hourly traffic speed in tunnel is 50 ~ 100km/h, and $70cm^3/m^3$ in Technical Report 2004. Therefore, the standard of ventilation inside the tunnel and the standard of air quality outside the tunnel are also the factors affecting the implementation of ventilation system in stages.

The feasibility and rationality of the staged implementation ofa ventilation system will be affected by the degree of difficulty of the staged implementation of such a tunnel structure as the reservation or upgrading, connecting duct and air opening of ventilation system, and the economy of the staged implementation of fans, power supply and distribution facilities and other facilities.

2 Ventilation equipment is the main facility for smoke control and smoke extraction inthe case of a tunnel fire. In the case of a fire, controlling the air velocity and smoke flow in the tunnel and providing corresponding fresh air can provide favorable environment conditions for drivers and rescue workers to escape and rescue.

3.1.4 The rational of the ventilation system shall be assessed according to the current actual traffic volume and traffic composition in upgrading tunnels and implementing the second stage of a ventilation system.

***Background*:**

The traffic volume and traffic composition used in the ventilation design of newly-built tunnels are mainly derived from the forecast data provided in the feasibility study report of a project. A large number of engineering surveys show that, due to various reasons, after the completion ofa tunnel, the actual traffic volume and traffic composition are significantly different from the forecast value in the forecast year corresponding to the project feasibility study report, and the ventilation system designed pursuant to the forecast traffic volume and traffic composition may have surplus or insufficient ventilation capacity. Therefore, as for the upgraded tunnels and the tunnels with ventilation facilities implemented in stages, their ventilation system shall be assessed in accordance with the current traffic volume and traffic composition.

3.1.5 Ventilation planning shall be based on the impact of surroundings and the bypass flow of polluted air in adjacent tunnels on the ventilation effect in a tunnel. The impact of the direct discharge of polluted air in a tunnel on surroundings shall be demonstrated when environmental protection is required in the area surrounding the tunnel site.

Background:

The polluted airwithin the tunnel site area increases the background concentration of pollutants in the air, which will cause secondary pollution in a tunnel, such as the tunnel passing through the area with serious environmental pollution, and the bypass flow pollution in adjacent tunnels. If the background concentration of pollutants is not taken into account, the ventilation capacity will be insufficient, resulting in potential safety hazards. Therefore, the impact of such environmental conditions on tunnel ventilation must be considered.

For the tunnel with environmental protection requirements in environmentally sensitive area, such as an urban tunnel, a tunnel passing through a plant and animal nature reserve, or a tunnel passing through densely populated areas, the pollution air discharged from a tunnel portal and/or ventilation tower may affect surrounding residents, animals and plants. In these cases corresponding measures must be taken to avoid or minimize adverse impacts on the surroundings such as air emissions and adding a purification device after technical demonstration.

3.1.6 The average longitudinal grade of the tunnel with a length $L > 5000$m shall not be greater than 2.0%; and the inlet line longitudinal grade along tunnel traffic direction shall be the same as the slope inside the tunnel.

Background:

Road Tunnel Technical Standard and Description on Ventilation by Japan Road Association (Oct. 2010) states, "the longitudinal grade of the long tunnel or extra-long tunnel with large air volume flow shall be preferably controlled less than 2%". These *Guidelines* are slightly more restrictive as China's motor vehicle exhaust emissions, especially the motor vehicle exhaust emissions on the national main trunks, are higher than Japan.

In the determination of longitudinal grade, not only the tunnel but also the front and rear connecting sections of tunnel must be considered, and they shall be fully demonstrated as a whole. The reason lies in that, even if the tunnel is flat, if the front part of the tunnel is uphill sharply, the traffic flow will accelerate before entering the tunnel, leading to the increase of exhaust and flowing into the tunnel, accordingly leading to the increase of pollutants in tunnel, and forming adverse conditions for ventilation.

3.1.7 Ventilation design of a highway tunnel shall include a comprehensive planning of daily operation ventilation facilities and disaster prevention ventilation facilities.

***Background*:**
Daily operation and disaster prevention ventilation facilities may be set up together or separately. In engineering practice, the daily operation fan shall be used as the disaster prevention fan as much as possible, so as to reduce the installed power of the ventilation system and ensure an effective and reliable operation of the disaster prevention fan. When longitudinal ventilation is used in the daily operation of the tunnel, but the smoke exhaust length and other criteria do not meet the requirements of disaster prevention and smoke exhaust, an independent smoke exhaust system can also be set up, taking into account the economy of operation and the safety of disaster prevention. Therefore, in order to meet the safety and economy of tunnel operation, ventilation design must be a comprehensive planning on whether daily operation and disaster prevention ventilation facilities are combined.

3.1.8 The ventilation design of a highway tunnel shall specify the number and location of fans in daily operation and fire conditions respectively.

***Background*:**
For the tunnels with mechanical ventilation, the fan is usually the largest electrical facility in the tunnel. The number of fans running and the load level of power supply are different under different working conditions. The combination and configuration of fans under fire conditions are proposed to reasonably determine the power supply load class of fans and allocate corresponding power supply and distribution facilities and control facilities, so as to ensure safe operation and reduce investment in power supply and distribution facilities.

3.1.9 The ventilation system of service tunnel and underground fan room shall adopt positive pressure ventilation mode.

***Background*:**
Service tunnel is set in parallel with the main tube of a tunnel to realize operation ventilation, smoke prevention and extraction, personnel evacuation and rescue, laying of various pipelines and other functions.

In case of fire ina tunnel, the service tunnel and underground fan room which may be used for evacuation and rescue are ventilated by mechanical means to form positive pressure ventilation and prevent fire smoke from the main tube from invading the above areas.

3.2 Ventilation survey

3.2.1 The ventilation design of a highway tunnel shall be based on the survey of the traffic, meteorology, environment, topography, topographic features and geology in the area where the tunnel is to be located.

3.2.2 The traffic survey for the ventilation design of a highway tunnel shall include:

1 Traffic volume, traffic composition, traffic congestion, pedestrian status and others of the segment where the tunnel is located at in the forecast year;

2 The composition of vehicles of different fuel types passing through the tunnel; and

3 Traffic peak hours and traffic rules of the segment where the tunnel isto be located.

***Background*:**

1 Traffic volume and traffic composition are the key parameters for the ventilation design ofa tunnel. The traffic composition used in the design includes the percentage of hybrid vehicles for each forecast year and whether it is the percentage of hybrid vehicles or PCU.

2 According to different engines, motor vehicles are mainly divided into gasoline vehicles and diesel vehicles. The particulate matters produced by diesel vehicles will have a greater impact on the ventilation for a tunnel, than a gasoline vehicles as its composition of emissions are different from that of diesel vehicles. Therefore, the proportion of diesel and gasoline vehicles shall be surveyed to improve the accuracy of required air volume flow in a tunnel.

The surveyresults demonstrate that the general proportion of various motor vehicles' engine types in China at present are as shown in Table 3-1. For the upgrading and extension of the tunnel and the staged implementation of the second stage of ventilation system, it is possible to carry out an on-site survey on the real-time traffic conditions to obtain the proportion of diesel and gasoline vehicles.

Table 3-1 Proportion of engine types of hybrid vehicles

Vehicle Type	Passenger car	Small truck	Large bus	Medium truck	Large truck	Container & articulated trailer
Diesel engine (%)	10	30	100	80	100	100
Gasoline engine (%)	90	70	0	20	0	0

3 The survey on the traffic peak hours and traffic rules of the segment where the tunnel is located is to reasonably select the most disadvantageous conditions and control ventilation size.

3.2.3 The meteorological survey for the ventilation design of highway tunnel shall include:

1 Natural air velocity oftunnel site area, air diffusion at tunnel portal or ventilation tower location;

2 Air pressure, wind direction, air velocity or temperature at tunnel portal and ventilation tower location; and

3 Special meteorological condition.

Background:

Natural air velocity, wind direction, air pressure and temperature are important parameters for ventilation calculations and selection of equipment for the tunnel site area. After the tunnel is put into use, the air pressure difference between two tunnel portals and between the tunnel portal and aboveground tower of any ventilation shaft will have an impact on the ventilation effect of the tunnel. Therefore, this Clause is for the purpose of accurately calculating ventilation system pressure and selecting fan model.

When the polluted air is discharged directly from tunnel portals or ventilation towers, the survey on local air velocity, wind direction and diffusion conditions near the tunnel portal can provide basic data for adopting a reasonable engineering scheme in order to avoid an impact on the environment or the reverse flow of polluted air into adjacent tunnels.

For tunnels in freezing, foggy, snowy, humid and high-temperature areas, relevant meteorological factors shall be surveyed to analyze the adverse impacts onthe ventilation system. The tunnel structure and ventilation system shall be designed reasonably to ensure the safe operation of tunnel.

3.2.4 The environmental survey for the ventilation design of a highway tunnel shall include:

1 Sensitive topographic features around tunnel portals or ventilation towers, and ambient air background concentration in the tunnel site area; and

2 The geology of ventilation shaft and fan room, and the topography and topographic features of the area where the ventilation tower is located.

Background:

The survey of the sensitive topographic features around tunnel portals or ventilation towers is to understand the environmental protection requirements of the tunnel site area, and the survey of background concentration is to understand the extent of secondary polluted air in the tunnel. Geology, topography and topographic features are important factors affecting the rationality and safety for the setting of ventilation shaft, fan room and ventilation tower. Therefore, it is necessary to carry out environmental surveys and obtain relevant information for design.

3.3 Traffic volume

3.3.1 The DHV adopted in ventilation design shall be converted according to the design (forecast) AADT proposed in the feasibility study report of the segment where the tunnel is located at, and shall be in accordance with the following provisions:

1 The DHV coefficient should be based on the data provided in the feasibility study report. When the feasibility study report does not explicitly put forward this data, that of the tunnel in mountainous and hilly terrain is preferable to be 12%, level and rolling terrain 10%, and near town 9%.

2 The directional distribution factorfor a uni-directional tunnel should be taken according to the feasibility study report. When the feasibility study report does not explicitly put forward this value, 55% is recommended. The directional distribution factor of bi-directional tunnel in the longer uphill direction can be 60%.

3 When the DHV is larger than the maximum service volume of the segment where the tunnel is located at, the DHV converted by the maximum service volume should be adopted.

Background:

Traffic volume is one of the most importantinputs for tunnel ventilation design. In ventilation design, it is necessary to convert the traffic volume of PCU into the design PHV of hybrid vehicles in accordance with "Representative Vehicle Types and Vehicle Conversion Coefficient" in *Technical Standards for Highway Engineering* (JTG B01) and in addition to the specific traffic composition of projects as per the following steps:

Step 1: convert the AADT (pcu/d) in the forecast year proposed in the feasibility study report into the design PHV of PCU (pcu/h);

Step 2: respectively calculate the design PHV of PCU corresponding to each vehicle according to the traffic composition percentage proposed in the feasibility study report; and

Step 3: convert the traffic volume of PCU into the design PHV (veh./h) of hybrid vehicles in accordance with "Representative Vehicle Types and Vehicle Conversion Coefficient" in the*Technical Standards for Highway Engineering* (JTG B01).

1 After extensive engineering researches, the DHV coefficient proposed in the feasibility study report of the expressway varies from 9% to 12%. In order to avoid the waste of ventilation system caused by excessive DHV, this Clause is made according to the summary of extensive engineering surveys and feasibility study reports.

2 To facilitate the calculation of traffic volume, this Clause is made in accordance with the*Technical Standards for Highway Engineering* (JTG B01).

3 The engineering surveys show that the "forecast traffic volume in xx (year)" provided in the feasibility study report is quite different from the actual traffic volume in the corresponding year after the completion of the project. The actual traffic volume of highways in underdeveloped and backward areas is usually much smaller than that forecast before construction. For highways in economically developed areas, the actual traffic volume is often greater than the forecast or designed. Therefore, to avoid excessive design ofa ventilation system, when the DHV is greater than the maximum service volume of the segment where the tunnel is located at, in ventilation calculation, the corresponding level of service of highways at all levels, and the maximum service volume at the corresponding design speed pcu/(h · In) shall be converted as the design PHV of hybrid vehicles by using traffic lane width, lateral clear width, the mix of large vehicles, driver condition and other factors.

3.3.2 Traffic congestion may not be considered for the tunnels with a length L≤1000m; for the tunnels with a length L > 1000m, the congested length of each lane should be 1000m. The following cases may be deemed as congested traffic:

1 The average driving speed on each lane in the expressway tunnel is no more than 30km/h.

2 The average driving speed on each lane in the Class-I highway tunnel is no more than 20km/h.

3 The average driving speed on each lane in the Class-II, Class-III and Class-IV expressway tunnel is no more than 10km/h.

Background:

Different countries and international organizations define traffic congestion differently. The *Road Tunnel Technical Standard and Description on Ventilation* by Japan Road Association (Oct. 2010) puts forward that "the driving speed is less than 20km/h in case of congested traffic". Technical Report 2004 of PIARC C5 states that the design conditions are defined as congested traffic speed of 10km/h and standstill segment in ventilation design. In order to avoid excessive ventilation design of long tunnels, it is feasible to avoid congested or standstill traffic of the whole tunnel through the traffic control system. PIARC C5 gives the corresponding traffic volume as shown in Table 3-2.

Table 3-2 Average peak hourly traffic density as stipulated in *Highway Tunnel Automobile Exhaust and Required Air Volume Flow* by PIARC C5

Items		Average peak traffic density (pcu/km) / traffic flow per lane (pcu/h)							
		Rural tunnel				Urban tunnel			
Traffic condition	Vehicle speed (km/h)	Uni-directional		Bi-directional		Uni-directional		Bi-directional	
		pcu/km	pcu/h	pcu/km	pcu/h	pcu/km	pcu/h	pcu/km	pcu/h
Fluid	60	30	1800	23	1400	33	2000	25	1500
Congested	10	70	700 ~ 850	60	600	100	1000	85	850
Standstill	0	150	—	150	—	165	—	165	—

Through a comprehensive survey on the operation of highway tunnels in China, and a comprehensive consideration on the above data analysis conclusion and the provisions of *Technical Standards for Highway Engineering* (JTG B01), and in combination with the suggestions from relevant domestic scholars, this Clause defines the average driving speed in case of congested traffic in tunnel according to different classes of highways.

A highway tunnel with a length over 1km is generally provided with traffic monitoring equipment, and the probability of traffic congestion with a length over 1km in the rural highway tunnel is low, so the ventilation design shall cover the function of traffic monitoring system rather than the traffic congestion with a lengthen over 1km, otherwise the excessive ventilation facilities will be idle for a long time (or even forever), resulting in waste. PIARC Report 1995 also points this out. Therefore, this Clause is made on the basis that the congested traffic in a tunnel shall be considered "per lane" according to the technical report of PIARC.

3.3.3 The traffic volume in case of fire condition shall be calculated as per the following principles:

1 Vehicle speed in such condition should be 0km/h.

2 It should be considered that the fire will break out at the terminal position of independent smoke exhaust zone inuni-directional tunnel, and at the middle point of bi-directional tunnel.

3 The traffic volume of tunnel is the sum of the number of vehicles stuck in the tunnel and the number of vehicles entering the tunnel subsequently. As for the number of vehicles entering the tunnel subsequently, it should be 5 minutes for theuni-directional tunnel, and 10 minutes for the bi-directional tunnel.

Background:

Generally, inthe case of a fire in uni-directional tunnels, the vehicles at the downstream segment from fire point to tunnel exit will leave the tunnel under normal conditions, while a certain number of vehicles will be detained at the upstream segment from tunnel entrance to fire point. These retained vehicles will form a greater resistance to smoke exhaust ventilation system; and the more vehicles are retained in the tunnel, the greater the ventilation resistance will be.

These retained vehicles are composed of the existing vehicles at fire point upstream segment at the moment of fire; and the vehicles entering the tunnel subsequently after the fire for the reason that the vehicles outside the tunnel did not know the fire has occurred inside the tunnel due to the traffic control lag.

In general, the long and extra-long tunnels of expressways and Class-I highways are equipped with perfect traffic monitoring systems or special administrations. The questionnaire survey shows that when a fire occurs in the tunnel, the control response time often lags around 5 minutes. Bi-directional tunnels are mainly Class-II, Class-III and Class-IV highway tunnels. When the middle point of these tunnels catch fire, mechanical smoke prevention and extraction system is in the worst case scenario, and such tunnels are not equipped with specialized administrations, so the time for finding and reporting a fire is relatively delayed, and the questionnaire survey shows that the control response time often lags about 10 minutes. In light of that, this Clause is established.

4 Ventilation Mode

4.1 Selection of ventilation mode

4.1.1 The establishment of mechanical ventilation in a highway tunnel may be preliminarily determined according to the following conditions:

1 Forbi-directional tunnel, when formula (4.1.1-1) is met, the mechanical ventilation may be set.

$$L \cdot N \geqslant 6 \times 10^5 \tag{4.1.1-1}$$

Where:

L—tunnel length (m);

N—design hourly volume (DHV) (veh./h).

2 Foruni-directional tunnel, when formula (4.1.1-2) is met, the mechanical ventilation may be set.

$$L \cdot N \geqslant 2 \times 10^6 \tag{4.1.1-2}$$

***Background*:**

Tunnel ventilation includes natural ventilation and mechanical ventilation. Such two formulas proposed in this Clause are the empirical formulas for determining whether mechanical ventilation is needed and can only be used as preliminary methods.

Natural ventilation is to realize the exchange of air inside and outside the tunnel through the air flow in the tunnel formed by meteorological factors and the fresh air brought by motor vehicles from outside the tunnel; while mechanical ventilation is to realize the exchange of air inside and outside the tunnel by making air flow by fans along the predetermined route.

4.1.2 Classification of mechanical ventilation modes may refer to Table 4.1.2.

Table 4.1.2 Classification of mechanical ventilation mode

Longitudinal ventilation mode	Semi-transverse ventilation mode	Full transverse ventilation mode	Combined ventilation mode
1) Longitudinal ventilation with full jet stream 2) Longitudinal ventilation with Saccardo nozzle 3) Longitudinal ventilation with supply and exhaust shafts 4) Longitudinal ventilation with exhaust shaft 5) Longitudinal ventilation with dust collector	1) Semi-transverse supply ventilation system 2) Semi-transverse exhaust ventilation system 3) Press-in type	1) Top supply and top exhaust 2) Bottom supply and top exhaust 3) Top supply and bottom exhaust 4) Sidewall supply and sidewall exhaust	1) Combined longitudinal ventilation 2) Longitudinal + semi-transverse ventilation 3) Longitudinal + point smoke extraction ventilation

***Background*:**

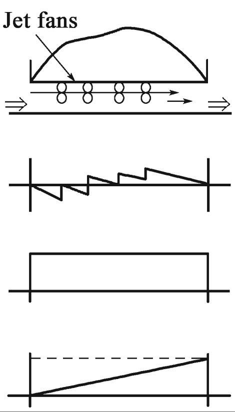
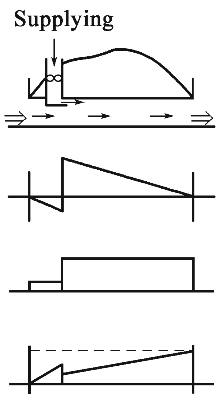
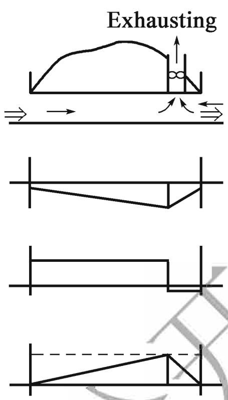
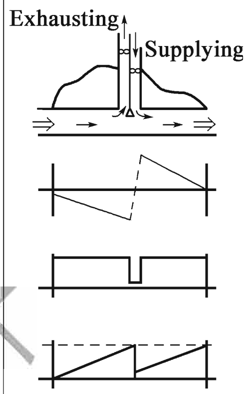
One or more ventilation modes may be combined to form a more reasonable ventilation mode based on tunnel conditions. At present, tunnel ventilation in China mainly consists of various longitudinal ventilation modes and their combinations. The ventilation mode integrating "longitudinal ventilation with supply and exhaust shafts + jet fan" is commonly adopted in the highway tunnels which have a length over 5000m and have been built in China, and the highway tunnel in Qinling-Zhongnan Mountain is a typical representative.

The basic characteristics of main ventilation modes under different traffic conditions are shown in Table 4-1 and Table 4-2.

Table 4-1 Characteristics of main ventilation modes(uni-directional tunnel)

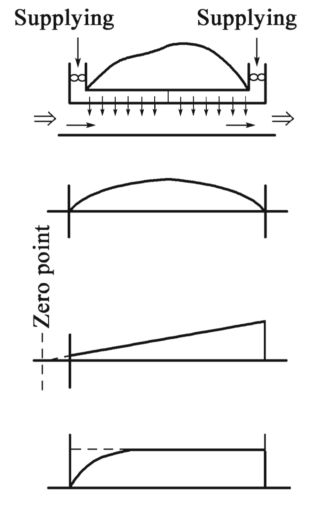
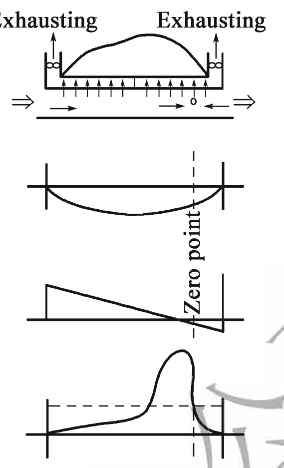
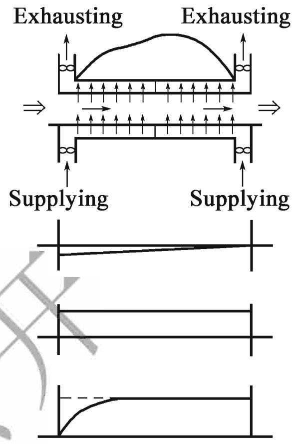
Ventilation mode	Longitudinal			
Basic characteristics	Ventilation flow moves longitudinally along the tunnel			
Representative form	Longitudinal ventilation with full jet stream	Longitudinal ventilation with Saccardo nozzle from tunnel portal	Longitudinal ventilation with exhaust shaft	Longitudinal ventilation with supply andexhaust shafts
Form characteristics	Pressure rise by jet fans	Air supply and pressure rise by jet stream	Air supply from both tunnel portals, and centralized exhaust in middle	Air supply and pressure rise by jet stream

continued

Ventilation mode		Longitudinal			
Sketch of ventilation system Pressure in tunnel Air velocity in tunnel Concentration distribution					
General characteristics	Applicable length under non-fire condition	Within 5000m	About 3000m	About 5000m	Unlimited
	Use of traffic air	Good	Good	Locally good	Good
	Noise	Loud	Loud at tunnel portal	Low	Low
	Fire treatment	Inconvenient in smoke extraction	Inconvenient in smoke extraction	Less convenient in smoke extraction	Less convenient in smoke extraction
	Engineering cost	Low	Reasonable	Reasonable	Reasonable
	Management and maintenance	Inconvenient	Convenient	Convenient	Convenient
	Implementation in stages	Easy	Not easy	Not easy	Not easy
	Technical difficulty	Not difficult	General	General	Less difficult
	Operating costs	Low	General	General	General
	Environmental protection at tunnel portal	Disadvantageous	Disadvantageous	Advantageous	General

Ventilation mode	Semi-transverse		Full transverse
Basic characteristics	Supply or exhaust from duct, or longitudinal exhausting or ventilating along the tunnel		Supply and exhaust ducts are established respectively. Ventilation flow moves transversely in tunnel.
Representative form	Semi-transversesupply ventilation system	Semi-transverseexhaust ventilation system	
Form characteristics	Air supply fromsupply duct	Air exhaust from exhaust duct	

continued

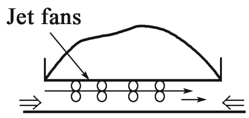
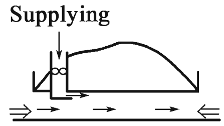
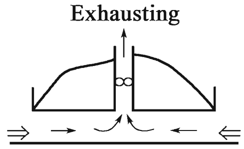
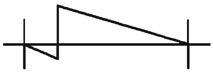
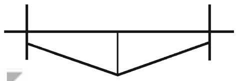
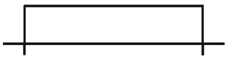
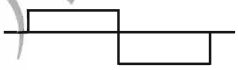
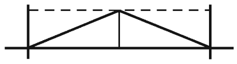
Ventilation mode		Semi-transverse		Full transverse
Sketch of ventilation system Pressure in tunnel Air velocity in tunnel General characteristics				
General characteristics	Applicable length	3000 ~ 5000m	About 3000m	Unlimited
	Use of traffic air	Good	Poor	Poor
	Tunnel environment	Lower noise	Lower noise	Lower noise
	Fire treatment	Convenient in smoke extraction	Convenient in smoke extraction	Effective in smoke extraction
	Engineering cost	High	High	Higher
	Management and maintenance	General	General	General
	Implementation in stages	Difficult	Difficult	Difficult
	Technical difficulty	Less difficult	Less difficult	Difficult
	Operating costs	High	High	Higher
	Environmental protection at tunnel portal	General	Advantageous	Advantageous

Note: The applicable length of each ventilation mode shown in the table refers to the reference value under normal circumstances.

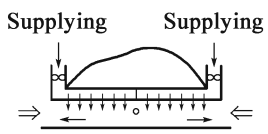
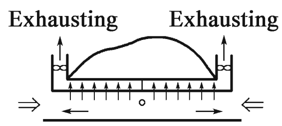
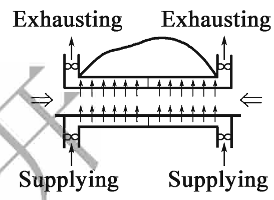
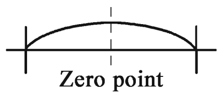
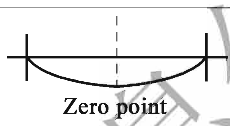
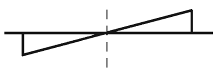
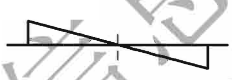
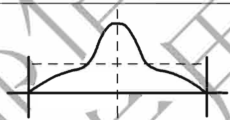
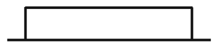
Table 4-2 Characteristics of main ventilation modes (bi-directional tunnel)

Ventilation mode	Longitudinal		
Basic characteristics	Ventilation flow moves longitudinally along the tunnel		
Representative form	Longitudinal ventilation with full jet stream	Longitudinal ventilation with Saccardo nozzle from tunnel portal	Longitudinal ventilation with exhaust shaft
Form characteristics	Pressure rise by jet fans	Air supply and pressure rise by jet stream	Air supply from both tunnel portals, and centralized ventilating in middle

continued

Ventilation mode		Longitudinal		
Sketch of ventilation system				
Pressure in tunnel				
Air velocity in tunnel				
Concentration distribution				
General characteristics	Applicable length	1500 ~ 3000m	About 1500m	About 4000m
	Use ofpiston wind	Poor	Poor	Poor
	Tunnel environment	Loud noise	Loud at tunnel portal	Low
	Fire treatment	Inconvenient in smoke extraction	Inconvenient in smoke extraction	Less convenient in smoke extraction
	Engineering cost	Low	Reasonable	Reasonable
	Management and maintenance	Inconvenient	Convenient	Convenient
	Implementation in stages	Easy	Not easy	Not easy
	Technical difficulty	Not difficult	General	General
	Operating costs	Low	General	General
	Environmental protection at tunnel portal	Disadvantageous	Disadvantageous	Advantageous

continued

Ventilation mode		Semi-transverse		Transverse
Basic characteristics		Air supply or exhaust from duct, or longitudinal exhaust or ventilation along the tunnel		Supply and exhaust ducts are established respectively. Ventilation flow moves transversely in tunnel.
Representative form		Semi-transversesupply ventilation system	Semi-transverseexhaust ventilation system	
Form characteristics		Air supply fromsupply duct	Air exhaust from exhaust duct	
Sketch of ventilation system				
Pressure in tunnel				
Air velocity in tunnel				
Concentration distribution				
General characteristics	Applicable length	3000m	About 3000m	Unlimited
	Use ofpiston wind	Poor	Poor	Poor
	Tunnel environment	Low	Low	Low
	Fire treatment	Less convenient in smoke extraction	Less convenient in smoke extraction	Convenient in smoke extraction
	Engineering cost	High	High	Higher
	Management and maintenance	General	General	General
	Implementation in stages	Difficult	Difficult	Difficult
	Technical difficulty	Less difficult	Less difficult	Difficult
	Operating costs	High	High	Higher
	Environmental protection at tunnel portal	General	Advantageous	Advantageous

Note: The applicable length of each ventilation mode shown in the table refers to the reference value under normal circumstances.

4.1.3 The selection for a highway tunnel ventilation mode shall be comprehensively based on the horizontal and vertical indexes, traffic volume, meteorological conditions, geomorphology, economy and other factors.

4.1.4 When longitudinal ventilation is adopted, longitudinal ventilation with full jet stream may be adopted for the uni-directional tunnel with a length $L \leq 5000m$ and the bi-directional tunnel with a length $L \leq 3000m$.

Background:

According to the statistics on the ventilation schemes of 200 and more extra-long tunnels that have been built or are under construction in China, the tunnels (40 tunnels in total) with a length over 5000m generally adopt thelongitudinal ventilation with supply and exhaust shafts, while the extra-long tunnels with a length less than or equal to 5000m generally adopt the longitudinal ventilation with full jet stream.

For theuni-directional tunnel with a length $L > 5000m$ and the bi-directional tunnel with a length $L > 3000m$, when the longitudinal ventilation with full jet stream may be adopted by the theoretical calculation, it is necessary to give serious consideration on adopting the longitudinal ventilation with full jet stream or not in combination with the tunnel possible traffic condition, comprehensive capability for smoke extraction and fire control, tunnel management institutional capacity and other technical demonstrations. Longitudinal ventilation with full jet stream is an inductive ventilation mode rising pressure by jet fans, and the pressure of a single set of fans rises slightly. When the air pressure and the natural air pressure are greater than the pressure rise of a single set of jet fans, entrainment effect of a single set of jet fans will happen, lowering the efficiency of ventilation system, lacking of ventilation capacity, and causing air flow with a loss of authority and no means to control the air flow in a confined underground space.

4.1.5 For longitudinal ventilation with supply and exhaust shafts, the number of ventilation shafts and the sectional length of a tunnel shall be based on the tunnel length, smoke prevention and exhaust requirements, ventilation shaft setting conditions, construction and operation costs, and others.

Background:

The number of ventilation shafts is closely related to tunnel length and the need for disaster prevention and smoke extraction, which affects the ventilation effect and engineering cost; and the reasonable setting of ventilation shafts may improve the safety and economy of tunnel operation. According to the surveys and statistics on the existing tunnels that adopt thelongitudinal ventilation with supply and exhaust shafts in China, 1 ventilation shaft shall be usually set in the tunnel with a length of $5000m < L \leq 8000m$, 1 or 2 ventilation shafts in tunnel with a length of $8000m < L \leq 12000m$, 2 or 3 ventilation shafts in tunnels with a length of $12000m < L \leq 16000m$, and 3 or more ventilation shafts in tunnels with a length of L > 16000m.

4.2 Tunnel ventilation requirements

4.2.1 The design air velocity of:

4.2.1.1 a uni-directional tunnel should generally not be greater than 10.0m/s and not greater than 12.0m/s in special cases.

4.2.1.2 a bi-directional tunnel should not be greater than 8.0m/s; and

4.2.1.3 of tunnels with dedicated sidewalks shall not be greater than 7.0m/s.

Background:
The design air velocity mentioned in this Clause refers to the average air velocity in tunnel traffic or pedestrian space; and the traveled and pedestrian tunnels refer to these tunnels with dedicated sidewalks.

The design air velocity ofuni-directional tunnel is subject to the *Road Tunnel Technical Standard and Description on Ventilation* by Japan Road Association(Oct. 2010) and Norway *Design Code for Highway Tunnels*. The design air velocity of bi-directional tunnel for people and vehicles is subject to the *Road Tunnel Technical Standard and Description on Ventilation* by Japan(Oct. 2010) and PIARC Report.

In consideration of the complicated construction conditions, the tunnels which have no condition to be set up with ventilation shafts for sectional ventilation, or such engineering measures as expanding the tunnel cross section, adding or adjusting ventilation shaft, adding electrostatic dust removal equipment or changing ventilation mode for reducing the design air velocity in the whole tunnel or a segment of the tunnel to be less than 10.0m/s will lead to the sharp increase of construction or operation costs; or the design air velocity of the tunnels which have no construction condition to adjust ventilation scheme may be 10.0 ~ 12.0m/s under special circumstances.

4.2.2 The design ventilation direction of a bi-directional tunnel should be consistent with the driving direction with the longer uphill route, and the direction of ventilation flow in the tunnel should not be changed frequently.

Background:
In order to make better use of piston effect oftraffic and piston wind in tunnel, the direction of air

flow in the tunnel should not change frequently. For the single-tube bi-directional tunnel with the jet fan operating in the same positive direction as the main traffic direction, when the direction of the main traffic direction changes, the direction of the operating ventilation flow will change in order to make better use of the piston effect of traffic.

Moreover, in order to avoid the continuous change of ventilation pressure mode, the air flow direction of jet fan should not be frequently reversed. In a bi-directional tunnel, the natural wind direction may also constantly change. If the direction of fan jet is frequently reversed, the pressure mode will be constantly changing, which will complicate the ventilation system. At the same time, in view of the inertia of air flow, it will cause great energy loss and turbulence if it is often reversed.

4.2.3 Measures should be taken to avoid the bypass flow of polluted air between the adjacent portals of extra-long twin-arch tunnels or the extra-long twin-tunnel with narrow pillar. When the polluted air's bypass flow is unavoidable, the ventilation design shall cover the impact of the bypass flow.

***Background*:**
As for the extra-long twin-arch tunnels or the extra-long twin-tunnel with narrow pillar, thepolluted air's bypass flow between adjacent tunnels will affect the ventilation effect in tunnel, therefore, the corresponding measures should be taken to avoid the bypass flow of polluted air. For example, a separation wall can be set up or tall trees can be planted between two tunnels; and the longitudinal distance between the left and right tunnels may not be less than 10m as shown in Figure 4-1.

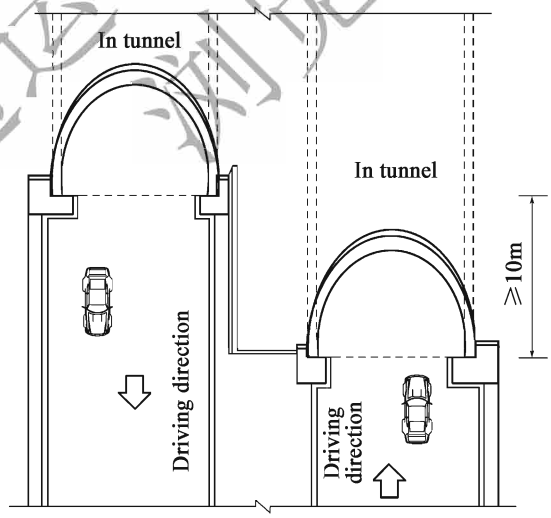


Figure 4-1 Layout of tunnel portal to avoid impact by bypass flow

4.2.4 When the polluted air discharged from the traffic exit of an upstream tunnel causes secondary pollution to a downstream tunnel, the ventilation mode of the upstream tunnel and downstream tunnel shall be considered comprehensively according to the pollution degree.

Background:

When the longitudinal distance between the upstream tunnel and downstream tunnel is relatively small, part of the polluted air discharged from the upstream tunnel exit is often taken into the downstream tunnel by traffic flow, which increases the background concentration of pollutants in the air at the downstream tunnel portal and causes secondary pollution to the downstream tunnel.

The domestic and overseas theoretical research achievements on polluted air' sbypass flow between the upstream or downstream tunnel portals, model scale ventilation experiment results and domestic on-site research achievements of polluted air' s bypass flow between the tunnel portals of a short tunnel show that generally when the longitudinal distance between the upstream and downstream tunnel portals is less than 100m, there exists the problem of polluted air' s bypass flow between upstream and downstream tunnel, especially that upstream and downstream tunnels containing extra-long tunnels may confront with polluted air' s bypass flow.

5 Ventilation Standard

5.1 General

5.1.1 The safety standard of highway tunnel ventilation design shall focus on diluting the particulate matters from motor vehicles. If necessary, dust pollution caused by motor vehicles in tunnel can be taken into account.

5.1.2 The health standard of highway tunnel ventilation design shall focus on diluting CO from motor vehicles. If necessary, some measures may be taken to dilute NO_2.

5.1.3 The comfort standard of highway tunnel ventilation design shall focus on diluting the unpleasant odor from motor vehicles by ventilating. If necessary, some measures may be taken for excessive heat.

***Background*:**
The main targets in tunnel ventilation as mentioned through 5.1.1 to 5.1.3 are CO, NO_2, particulate matters, and the unpleasant odor in air. The ventilation standards involved in *the Guidelines* are mainly the summary of the research results of highway tunnel ventilation standards for the areas with an altitude below 3000m.

The harmful substances in the vehicle emissions in highway tunnels include CO, NO_2, Pb, CO_2, SO_2, HCHO and particulate matters. Among which, CO and NO_2 have obvious impacts on human health. As a result, one of the main indexes in ventilation design is to control their concentration (namely the concentration of CO and NO_2) within a limit for safety.

With the increasing development of diesel vehicles, to ensure adequate visibility and solve the problem of particulate matters, the Tunnel Technical Committee of PIARC proposed a set of calculation methods for the dilution of diesel vehicle particulate matters on the basis of studies of

Japan, France and other countries in 1975.

The Report of 18th General Meeting of Tunnel Technical Committee of PIARC stated the comfort standards, namely diluting the unpleasant odor in air.

With the reduction of pollutants from automobile exhaust, particulate matter and dust generated by tyres, braking and road wear have become important factors for pollution in tunnels. Moreover, some countries have used nitrogen oxide as a control factor for polluted air in tunnels. In the context of the large number of highway tunnels and the fast development of economy and technology in China, for diluting dust and NO_2 pollution, removing excessive heat, etc. in tunnels, *the Guidelines* is proposed only as optional clauses, not the object that shall be considered in tunnel ventilation design in principle, and corresponding studies shall be conducted when necessary.

5.2 Designconcentration of particulate matters

5.2.1 The design concentration of particulate matters, K, shall be in accordance with the following provisions:

1 When the sodium light source with a color rendering index 33 ≤ Ra ≤ 60 and a correlated color temperature of 2000 ~ 3000K is adopted, the designconcentration of particulate matters shall be as per Table 5.2.1-1.

Table 5.2.1-1 Designconcentration of particulate matters (sodium light source)

Design speed V_t (km/h)	≥90	$60 \leq V_t < 90$	$50 \leq V_t < 60$	$30 < V_t < 50$	$V_t \leq 30$
Designconcentration of particulate matters (m^{-1})	0.0065	0.0070	0.0075	0.0090	0.0120*

Note: * Traffic control or tunnel closure or other measures shall be taken under this condition.

2 When the fluorescent tube or LED light with a color rendering indexRa ≥ 65 and a correlated color temperature of 3300 ~ 6000K is adopted, the design concentration of particulate matters shall be as per Table 5.2.1-2.

Table 5.2.1-2 Designconcentration of particulate matters (fluorescent tube or LED light)

Design speed V_t (km/h)	≥90	$60 \leq V_t < 90$	$50 \leq V_t < 60$	$30 < V_t < 50$	$V_t \leq 30$
Designconcentration of particulate matters (m^{-1})	0.0050	0.0065	0.0070	0.0075	0.0120*

Note: * Traffic control or tunnel closure or other measures shall be taken under this condition.

Background:

"Designconcentration of particulate matters" is the degree of polluted air caused by particulate matters; and it is determined by measuring the transmittance of light through particulate matters in polluted air at a distance of 100m, and it is also called as 100m transmittance and the indicator of visibility in tunnel. It is defined in *Road Tunnel Technical Standard and Description on Ventilation* by Japan Road Association (Oct. 2010) as "design concentration of soot" and 100m transmittance indicated by percentage. In PIARC Report, "attenuation coefficient K" is used to indicate visibility.

Technical Report 2004 of PIARC-"*Road Tunnels: Vehicle Emissions and Air Demand for Ventilation*" states the design standards for traffic condition and visibility as well as the recommended correspondence between visibility transmittance and attenuation coefficient K in Table 5-1.

Table 5-1　Ventilation limits in Technical Report 2004 of PIARC

Traffic condition	Visibility	
	Attenuation coefficient K	Transmittance S (at a distance within 100m)
	$10^{-3}m^{-1}$	%
Normal peak traffic (50 ~ 100km/h)	5	60
Daily congested or standstill lanes	7	50
Less congested and standstill	9	40
Maintenance in the tunnel under operation as planned	3	75
Tunnel closure	12	30

The control status of the in-tunnel environment corresponding to the designconcentration of particulate matters under different traffic conditions is as follows:

$K = 0.0050 \sim 0.0030m^{-1}$, indicating the air in tunnel is clean and the visibility is hundreds of meters;

$K = 0.0070 \sim 0.0075m^{-1}$, indicating there is slight smoke in tunnel;

$K = 0.0090m^{-1}$, indicating there is smoky air in tunnel; and

$K = 0.0012m^{-1}$ is the limit, indicating that the air in tunnel is unpleasant, but the visibility meets the safe stopping sight distance.

The designconcentration of particulate matters is related to vehicle speed or safe stopping sight distance as well as the in-tunnel luminance (or illuminance) and light source, as detailed in Table 5-2. After extensive testing, Japanese lighting experts obtained the relation among the transmittance of light through particulate matters, vehicle speed, illumination and light source as shown in Figure 5-1.

Table 5-2 Relation among design speed, average luminance of road surface andconcentration of particulate matters

Design speed (km/h)	100	80	60	40
Average luminance of road surface (cd/m^2)	9.0	4.5	2.5	1.5
K (m^{-1})	0.0069	0.0070	0.0075	0.0090

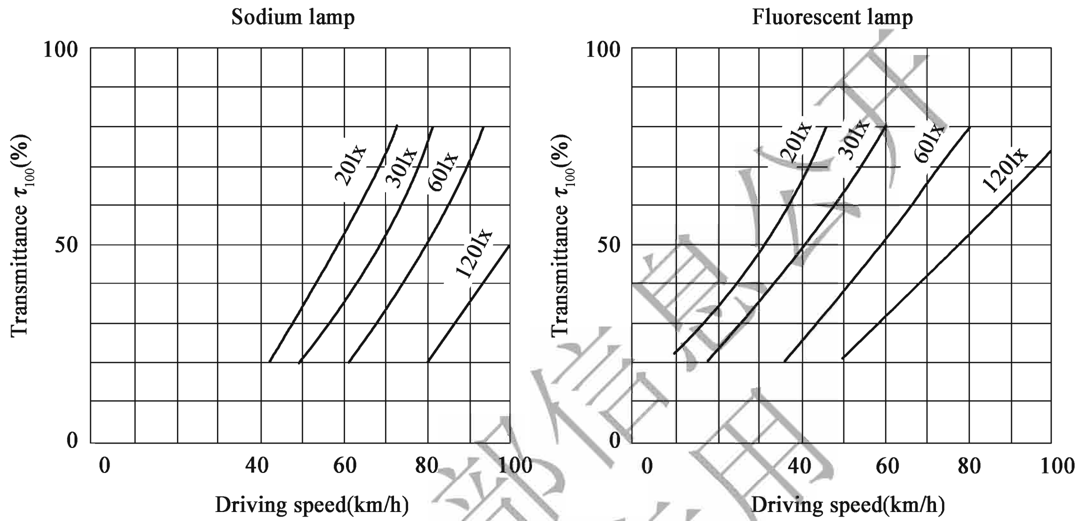


Figure 5-1 Relation among transmittance, driving speed, illuminance and light source

Theconcentration of particulate matters under the condition with " * " in Table 5.2.1-1 & Table 5.2.1-2 is $0.012m^{-1}$. When the concentration of particulate matters in the tunnel is $0.0120 m^{-1}$, the air in tunnel is unpleasant. In order to ensure the safety of traffic in tunnel, traffic control and other measures must be taken.

5.2.2 Where the single-tube uni-directional traffic is altered as single-tube bi-directional traffic temporarily, the allowable concentration of particulate matters in tunnel shall not be more than $0.012m^{-1}$.

5.2.3 Where the maintenance and repairing are conducted in tunnel, the allowable concentration of particulate matters at operation zone shall not be more than $0.0030m^{-1}$.

***Background*:**
Theallowable concentration of particulate matters in a tunnel put forward in clauses 5.2.2 through 5.2.3 shall refer to the recommended value in Technical Report 2004 of PIARC.

5.3 Design concentration of CO and NO_2

5.3.1 The design concentration of CO and NO_2 in tunnel shall be in accordance with the following provisions:

1 Under normal traffic condition, the design concentration of CO in tunnel mayrefer to Table 5.3.1.

Table 5.3.1 Design concentration of CO

Tunnel length(m)	≤1000	>3000
δ_{CO} (cm^3/m^3)	150	100

Note: when the tunnel length is 1000m < L ≤ 3000m, the linear interpolation method may be adopted for value calculation.

2 In case of congested traffic, the average design concentration of CO (δ_{CO}) at congested zone may be 150cm^3/m^3, and the duration should not be longer than 20 minutes.

3 The average design concentration of NO_2 (δ_{NO_2}) in tunnel within 20 minutes may be 1.0cm^3/m^3.

***Background*:**

In a simpler way, this Clause tries to reflect the conclusion ofMay's Tests: CO concentration, duration and activity status are closely related; and it is simple and reasonable to reflect the duration by tunnel length.

1 From 1994 ~ 1996, a large number of field measurements were carried out for Chongqing Zhongliang Mountain Tunnel at G85 Chongqing-Kunming Expressway. During the actual measurement, a fleet of vehicles with traffic volume and vehicle type combination fully consistent with the original design conditions are specially formed to test the effectiveness of ventilation. When all the fans in the uphill tunnel of Zhongliang Mountain left line were running, the measured average concentration of CO was only 42cm^3/m^3 (uni-directional traffic) and 68cm^3/m^3 (bi-directional traffic), which are 28% and 45% of the design value specified as 150cm^3/m^3. In 2010, the design PHV of Zhongliang Mountain Tunnel generally varied from 1800 to 2400veh./h, and traffic jam appears regularly. Relevant authorities once again measured the operating environment in the tunnel. Under normal traffic and different quantities of fans operating in the uphill tunnel, the CO concentration in the tunnel was 11.3 ~ 40cm^3/m^3; and in the downhill tunnel, the CO concentration in the tunnel was only 11.0cm^3/m^3 under the condition of normal traffic and no fan operating.

Technical Report 2004 of PIARC C5-Road Tunnels: Vehicle Emissions and Air Demand for Ventilation gives recommendations as indicated in Table 5-3.

Table 5-3 Ventilation limits in Technical Report 2004 of PIARC C5

Traffic condition	CO concentration(cm^3/m^3)	
	Design year	
	1995	2010
Normal peak traffic(50 ~ 100km/h)	100	70
Daily congested or standstill lanes	100	70
Less congested and standstill	150	100
Maintenance in the tunnel under operation as planned	30	20
Tunnel closure *	250	200

Note: the value marked with * is for tunnel operation only rather than ventilation design.

The CO design concentration mentioned herein is the recommended value in Technical Report 2004 of PIARC C5 and properly adjusted pursuant to the traffic conditions of China. In view of the traffic emissions standards of China lagging behind the EU for 5 ~ 7 years, correspondingly, the CO design concentration in tunnel mentioned in sub-clause 1 of clause 5.3.1 refers to that as stipulated in the 1995 standards in PIARC Report.

In the longitudinal ventilation system, CO concentration is distributed in a triangle, so people passing through the tunnel only experience the maximum CO "point concentration" in a very short time when they pass through the tunnel exit or other outlets. Therefore, the required air volume flow is not required to be based on the average concentration of the whole tunnel but the point concentration. Such has been pointed out in the relevant technical report of PIARC and the relevant technical standards of Norway, Japan and other countries.

2 Considering the technical progress of China's automobile industry and the situation that the traffic emissions standard lags behind the EU for 5 – 7 years, the criterion for the average CO design concentration in traffic congestion proposed in this paragraph refers to the 1995 standard in Technical Report 2004 of PIARC C5.

3 The NO_2 value recommended as mentioned in Technical Report 1999 of PIARC is adopted herein.

5.3.2 In the tunnel for pedestrians and vehicles passing through, the CO design concentration in tunnel shall not be more than $70cm^3/m^3$, and that of NO_2 within 60 minutes shall not be more than $0.2cm^3/m^3$.

Background:

The design concentration of CO and NO_2 specified in this Clause shall meet the minimum health standard for pedestrians to pass through the tunnel. In general, the design is carried out according to the limits proposed, which can provide the environmental conditions for pedestrians to pass through the tunnel safely and effectively control the ventilation size. When the health standard in tunnel is raised, that is, the design concentration of CO and NO_2 is lower than the limits, the size of ventilation system will be increased. For economic consideration, the design concentration of CO and NO_2 may be the limit.

For pedestrian tunnels, the design concentration of CO refers to the ventilation standard proposed by PIARC in Technical Report 1999; and the design concentration of NO_2 refers to the ventilation standards of Belgium and Sweden. Highway tunnels prohibit mixed traffic of pedestrians and vehicles, but there are such cases in China's low-class highway tunnels, so this Clause is made accordingly.

5.3.3 Where the maintenance and repairing are conducted in tunnel, the allowable concentration of particulate matters at operation zone in tunnel shall not be more than $30cm^3/m^3$, and that of NO_2 shall not more than $0.12cm^3/m^3$.

Background:

For tunnel maintenance and repairing, the allowable CO concentration proposed herein is subject to the recommended value in Technical Report 2004 of PIARC C5. The allowable concentration of NO_2 is $0.12cm^3/m^3$ per hour as per the second-level standard of nitrogen dioxide (NO_2) in document HF No. 1 [2000] issued by the State Environmental Protection Administration. The allowable concentration of CO and NO_2 in tunnel during maintenance and repairing mentioned in this Clause is for the management of tunnel during operation.

5.4 Ventilation requirements

5.4.1 The minimum air exchange frequency in tunnel shall not be less than 3 times per hour.

5.4.2 In the tunnel with longitudinal ventilation, the ventilation speed in the tunnel shall not be lower than 1.5m/s.

Background:

As for clauses 5.4.1 to 5.4.2, PIARC put forward in Technical Report 1995 that the uninterruptedair exchange frequency in tunnel should not be less than 5 times per hour; and as for the tunnel with small traffic volume or such tunnel is an extra-long tunnel, the uninterrupted air exchange frequency in tunnel may be 3 ~ 4 times per hour. In the tunnel with longitudinal ventilation, the ventilation speed in tunnel shall not be lower than 2. 5m/s. Some countries recommend that the air exchange frequency shall be 3 times per hour at least, or the minimum longitudinal air velocity in tunnel shall be 1. 5m/s. This Clause is formulated based on the above recommendations and taking into account the progress of China' s automobile industry, the improvement of automobile exhaust treatment technology and oil quality, and others.

To improve the comfort standard in tunnel, that is to increase theair exchange frequency or speed, will increase the size of the ventilation system. For the sake of economy, the air exchange frequency and speed in tunnel may refer to the standard.

6 Required Air Volume Flow

6.1 General

6.1.1 In the required air volume flow calculation, both the design hourly volume (DHV) and corresponding pollutants emissions from motor vehicles shall be matched with target year of each design.

***Background*:**
In the ventilation design of highway tunnels, thepollutants emissions from motor vehicles is an important factor that affects the size of the ventilation system. The calculation of the pollutants emissions from motor vehicles is mainly based on the corresponding traffic volume N and pollutants basic emission q of the target year of each design. With the development of China's automobile industry, continuous improvement and strictness of national regulations on automobile pollutant emissions and the continuous improvement of fuel quality, the basic emission of pollutants from motor vehicles will decrease year by year. Therefore, the determination of pollutants emissions shall be matched with the target year of each design.

6.1.2 For the tunnel ventilation design of a target year, the basic emission of pollutants from motor vehicles should be calculated from 2000 to the design target year at the declining rate of 2.0%, but the maximum reduction period should be no more than 30 years.

***Background*:**
Thebasic emission of pollutants from motor vehicles is related to factors like China's automobile engine technology, national regulations on automobile pollutant emissions and fuel quality.

Seen from relevant references about the controlled emission limits for different models at different stages of China's emission standards for vehicles, the yearly decline rates of main vehicle pollutants over the past ten years were generally over 10%. However, considering the restrictions on engine design and manufacturing technology, different vehicle conditions due to economic development levels in different regions, vehicle maintenance status and other factors, the yearly decline rate adopted should be conservative and 2% is recommended herein.

During 1999 to 2000, a series of vehicle pollutant emissions standards were implemented in China, so there are significant changes between the vehicle pollutant emissions limits before 1999 and after 2000. Currently, the majority of present vehicles are manufactured after 2000, so 2000 is recommended as the starting year herein.

6.1.3 Where new environment-friendly engine vehicles are among the traffic compositions of the segment where a tunnel is located at, the pollutants emissions should be calculated separately.

***Background*:**
With the technological progress ofthe automobile industry and increasing social demand for energy conservation, emissions reduction and environmental protection, the growing numbers of new environmentally friendly vehicles such as the large number of natural gas engine automobiles used in Chongqing and batches of hybrid electric buses used in Wuhan. Therefore, the ventilation design must take the application of new environmentally friendly vehicles and their percentages of total traffic volume and pollutants emissions into account.

6.1.4 For determination of the required air volume flow, the required air volume flow for dilution of particulate matters and CO shall be calculated separately for vehicle speed under working condition every 10km/h below the design speed. Moreover, the required air volume flow for congested traffic and ventilation shall be calculated and the higher one shall be the design required air volume flow.

***Background*:**
The installed power of ventilation system is related to factors such as the required air volume flow andpiston effect of traffic, while the required air volume flow and piston effect of traffic are related to the design speed of motor vehicles. Therefore, the determination of required air volume flow must be calculated separately for vehicle speed under working condition every 10km/h below the design speed.

6.2 Required air volume flow for particulate matters dilution

6.2.1 The basic emission of particulate matters in pollutants from motor vehicles in 2000 shall be $2.0m^2/(veh \cdot km)$.

Background:

Thebasic emission of particulate matters refers to the concentration of emissions from a medium diesel truck with a full load of 9.5t traveling for 1km.

By reference to Technical Report 2004 of PIARC and based on the research results of China's scientific research institutions, thebasic emission of particulate matters in pollutants from motor vehicles of 2000, q_{VI}, is 2.0m^2/(veh · km) for the calculation of the basic emission of particulate matters prescribed herein.

6.2.2 The particulate matter emissions shall be calculated by formula(6.2.2):

$$Q_{VI} = \frac{1}{3 \cdot 6 \times 10^6} \cdot q_{VI} \cdot f_{a(VI)} \cdot f_d \cdot f_{h(VI)} \cdot f_{iv(VI)} \cdot L \cdot \sum_{m=1}^{n_D} (N_m \cdot f_{m(VI)}) \qquad (6.2.2)$$

Where:

Q_{VI}—particulate matter emissions in tunnel(m^2/s);

q_{VI}—basic emission of the particulate matters of the design target year [m^2/(veh · km)], with the value calculated according to 6.1.2 and 6.2.1;

$f_{a(VI)}$—vehicle condition factor with consideration to particulate matters, with the value according to Table 6.2.2-1;

f_d—traffic density factor, with the value according to Table 6.2.2-2;

$f_{h(VI)}$—altitude factor with consideration to particulate matters, with the value according to Figure 6.2.2;

$f_{iv(VI)}$—longitudinal grade-vehicle speed factor with consideration to particulate matters, with the value according to Table 6.2.2-3;

L—tunnel length(m);

$f_{m(VI)}$—diesel vehicle type factor with consideration to particulate matters, with the value according to Table 6.2.2-4;

n_D—number of diesel vehicle types;

N_m—traffic volume of corresponding vehicle type (veh./h), with the value calculated according to Section 3.3 hereof.

Table 6.2.2-1 Vehicle condition factor $f_{iv(VI)}$ with consideration to particulate matters

Highway class	$f_{a(VI)}$
Expressway, Class-Ⅰ highway	1.0
Class-Ⅱ and below highway	1.2 ~ 1.5

Table 6.2.2-2 Traffic density factor f_d

Vehicle speed under working condition(km/h)	100	80	70	60	50	40	30	20	10
f_d	0.6	0.75	0.85	1	1.2	1.5	2	3	6

Table 6.2.2-3 Longitudinal grade-vehicle speed factor $f_{iv(VI)}$ with consideration to particulate matters

Vehicle speed under working condition (km/h)	Driving-direction longitudinal grade of the tunnel I (%)								
	−4	−3	−2	−1	0	1	2	3	4
80	0.30	0.40	0.55	0.80	1.30	2.60	3.7	4.4	—
70	0.30	0.40	0.55	0.80	1.10	1.80	3.10	3.9	—
60	0.30	0.40	0.55	0.75	1.00	1.45	2.20	2.95	3.7
50	0.30	0.40	0.55	0.75	1.00	1.45	2.20	2.95	3.7
40	0.30	0.40	0.55	0.70	0.85	1.10	1.45	2.20	2.95
30	0.30	0.40	0.50	0.60	0.72	0.90	1.10	1.45	2.00
10 ~ 20	0.30	0.36	0.40	0.50	0.60	0.72	0.85	1.03	1.25

Table 6.2.2-4 Diesel vehicle type factor $f_{m(VI)}$ with consideration to particulate matters

Passenger car, light truck	Medium truck	Heavy truck, bus	Articulated trailer, container vehicle
0.4	1.0	1.5	3

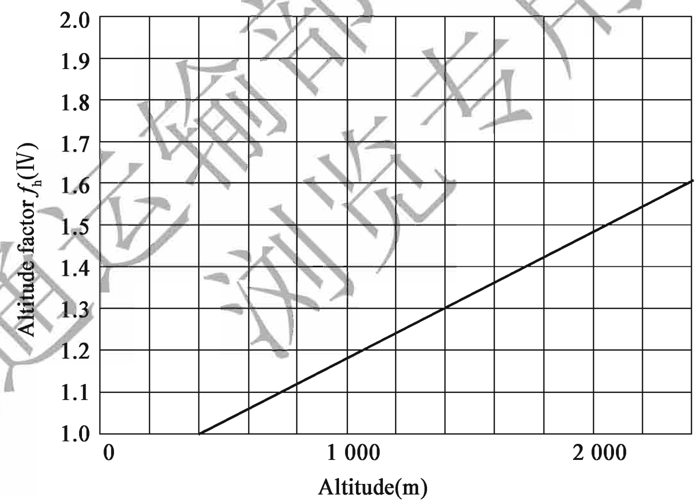


Figure 6.2.2 Altitude factor with consideration to particulate matters $f_{iv(VI)}$

Note: When the value exceeds the range shown, the straight line may be extended.

***Background*:**

This Clause mainly refers to the values recommended in current Japanese standards and technical reports of PIARC. The vehicle type factor $f_{m(VI)}$ is determined based on the relative vehicle weight and the $f_{m(VI)}$ of a medium diesel truck with a full load of 9.5 tons is taken as 1.0 in this Clause. The altitude factor $f_{h(VI)}$ refers to the values recommended in the *Technical Reference for Highway Tunnel Ventilation* by Japan Highway Public Corporation and *Road Tunnel Technical Standard and Description on Ventilation* by Japan Road Association (Oct. 2010).

6.2.3 The required air volume flow for particulate matters dilution shall be calculated by formula (6.2.3):

$$Q_{\mathrm{req(VI)}} = \frac{Q_{\mathrm{VI}}}{K} \tag{6.2.3}$$

Where:

$Q_{\mathrm{req(VI)}}$—required air volume flow for dilution of particulate matters in tunnel(m^3/s);

K— design concentration of particulate matters (m^{-1}), with the value according to Table 5.2.1-1 and Table 5.2.1-2;

Q_{VI}—particulate matter emissions in tunnel(m^2/s).

Background:

Theconcentration of particulate matters is not related to the duration. Even if the duration is short, the requirements for sight distance(visibility) shall also be met. Therefore, when the longitudinal ventilation mode is adopted, the required air volume flow for particulate matters dilution shall be calculated based on the "point concentration" at the tunnel exit or ventilation shaft air outlet.

6.3 Required air volume flow for CO dilution

6.3.1 The value of basic emission of CO in the pollutants of vehicle exhaust shall meet the following provisions:

1 Under normal traffic condition, the value ofbasic emission of CO in the pollutants of vehicle exhaust shall be $0.007m^3/(veh.\cdot km)$ for 2000.

2 Under congested traffic conditions where the vehicle is considered at idle speed, the value ofbasic emission of CO in the pollutants of vehicle exhaust shall be $0.015m^3/(veh.\cdot km)$ for 2000, but the congested segment calculated should not be longer than 1000 m.

Background:

After comprehensive consideration of China's implementation stage of vehicle emissions regulations, technological progress of the automobile industry, various complex conditions of in-use vehicles, China's vehicle population and national governance of energy conservation and emissions reduction, $0.007m^3/(veh.\cdot km)$ is taken as the value of basic emission of CO q_{CO} for 2000.

Under the idle running condition, the incomplete combustion in cylinder will increase CO emissions. Therefore, it is proposed to consider the vehicle at idle speed under congested traffic condition. According to the research results of China's scientific research institutions, $0.015m^3/(veh.\cdot km)$ is taken as the value of basic emission of CO in pollutants from motor vehicles for 2000.

6.3.2 The CO emissions shall be calculated by formula(6.3.2):

$$Q_{CO} = \frac{1}{3.6 \times 10^6} \cdot q_{CO} \cdot f_a \cdot f_d \cdot f_h \cdot f_{iv} \cdot L \cdot \sum_{m=1}^{n} (N_m \cdot f_m) \qquad (6.3.2)$$

Where:

Q_{CO}—CO emissions in tunnel(m^3/s);

q_{CO}—CO basic emission of the design target year [$m^3/(veh \cdot km)$], with the value according to Clause 6.1.2 and Clause 6.3.1;

f_a— vehicle condition factor with consideration to CO, with the value according to Table 6.3.2-1;

f_d—traffic density factor, with the value according to Table 6.2.2-2;

f_h—altitude factor with consideration to CO, with the value according to Figure 6.3.2;

f_m—vehicle type factor with consideration to CO, with the value according to Table 6.3.2-2;

f_{iv}—longitudinal grade-vehicle speed factor with consideration to particulate matters, with the value according to Table 6.3.2-3;

n—number of vehicle types;

N_m—traffic volume of corresponding vehicle type (veh./h), with the value calculated according to Section 3.3 hereof.

Table 6.3.2-1 Vehicle condition factor f_a with consideration to particulate matters

Highway class	f_a
Expressway, Class-I highway	1.0
Class-II and below highway	1.1 ~ 1.2

Table 6.3.2-2 Vehicle condition factor f_m with consideration to CO

Vehicle type	Diesel vehicle	Gasoline vehicle			
		Passenger car	Station wagon-light truck	Medium truck	Bus-articulated trailer
f_m	1.0	1.0	2.5	5.0	7.0

Table 6.3.2-3 Longitudinal grade-vehicle speed factor f_{iv} with consideration to CO

Design speed v_t (km/h)	Driving-direction longitudinal grade of the tunnel i (%)								
	−4	−3	−2	−1	0	1	2	3	4
100	1.2	1.2	1.2	1.2	1.2	1.4	1.4	1.4	1.4
80	1.0	1.0	1.0	1.0	1.0	1.0	1.2	1.2	1.2
70	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.2	1.2
60	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.2
50	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0

continued

Design speed v_t(km/h)	Driving-direction longitudinal grade of the tunnel i(%)								
	−4	−3	−2	−1	0	1	2	3	4
40	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
30	0.8	0.8	0.8	0.8	0.8	1.0	1.0	1.0	1.0
20	0.8	0.8	0.8	0.8	0.8	1.0	1.0	1.0	1.0
10	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8

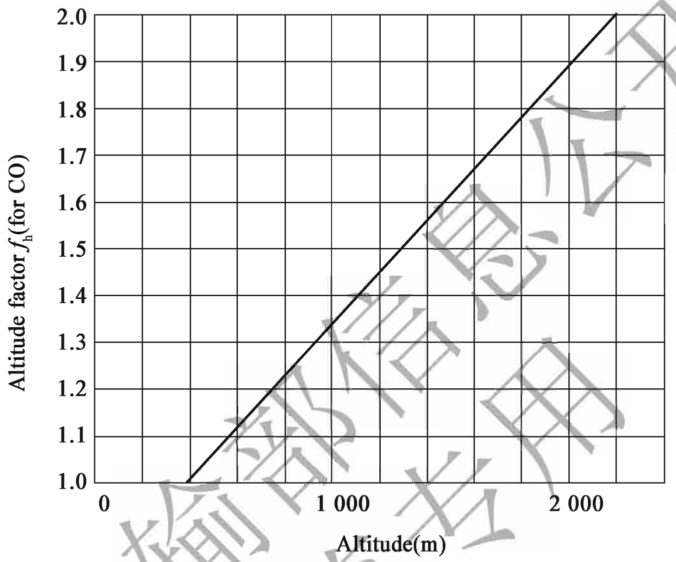
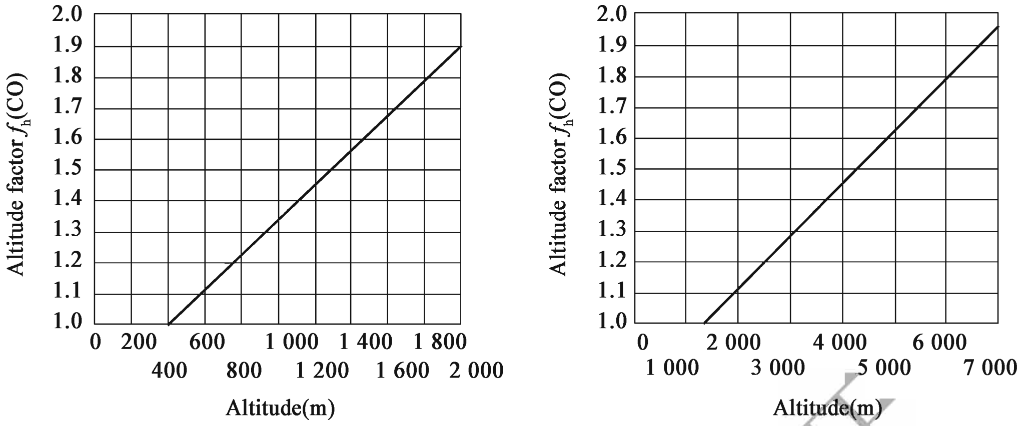


Figure 6.3.2 Altitude factor f_h with consideration to CO

***Background*:**

There are two expressions of the longitudinal grade-vehicle speed factor f_{iv}: divided into two groups, namely f_i and f_v; or combined into one, namely f_{iv}. The latter is adopted herein. Based on the values recommended in Technical Report 1987 and Technical Report 1991 of PIRAC, it has been integrated, adjusted and simplified here for ease of use.

There are two kinds of altitude factor f_h internationally. For one kind, both the influence of pollutants emissions increase due to the vehicle engine efficiency reduction in high altitude areas, and the influence of working air volume flow increase of fan in high altitude areas with thin air are taken into account. In essence, it is the product of emission correction factor and required air volume flow correction factor, so the f_h value is larger. For another kind, only the emission increase is taken into account, while the required air volume flow increase is calculated separately, so the value is smaller. The latter one is adopted in Switzerland, USA, etc. and the values are completely the same. See Figure 6-1. Only the correction of emission is considered in the altitude factor f_h herein.



a)Switzerland　　b)USA

Figure 6-1　Factorf_h abroad

6.3.3　The required air volume flow for CO dilution shall be calculated by formula(6.3.3):

$$Q_{req(CO)} = \frac{Q_{CO}}{\delta}\frac{p_0}{p}\frac{T}{T_0}10^6 \qquad (6.3.3)$$

Where:

$Q_{req(CO)}$—required air volume flow for diluting CO in tunnel(m^3/s);

Q_{CO}—CO emissions in tunnel(m^3/s);

δ—concentration of CO;

p_o—normal atmospheric pressure(kN/m^2),101.325kN/m^2;

P—atmospheric pressure at tunnel site(kN/m^2);

T_0—normal temperature(K),273K;

T—summer temperature at tunnel site(K).

Background:

For the calculation of required air volume flow for CO dilution, if the activity state(by car or foot or working) is the same, both the CO concentration and the duration shall be taken into account.

For formula(6.3.3), the design atmospheric pressure attunnel site may be acquired from the tunnel project feasibility study report, geological survey and other relevant materials. When the value is unavailable at design stage, it may be calculated by formula(6-1).

$$P = P_0 \times \exp\left(-\frac{h}{29.28T}\right) \qquad (6\text{-}1)$$

Where:

h—design altitude at tunnel site(m).

6.4 Required air volume flow for tunnel ventilation

6.4.1 The required air volume flow for tunnel ventilation shall be calculated by formula (6.4.1):

$$Q_{req(ac)} = \frac{A_r \cdot L \cdot n_s}{3600} \tag{6.4.1}$$

Where:

$Q_{req(ac)}$—required air volume flow for tunnel ventilation (m^3/s);

A_r—tunnel free cross-sectional area (m^2);

n_s—minimum air exchange frequency of the tunnel, with the value according to 5.4.

6.4.2 For tunnels adopted with longitudinal ventilation, the required air volume flow for ventilation shall be calculated by formula (6.4.1) and formula (6.4.2), and the greater one shall be adopted for uninterrupted volume of the tunnel space.

$$Q_{req(ac)} = v_{ac} \cdot A_r \tag{6.4.2}$$

Where:

v_{ac}—ventilation speed in tunnel, which shall not be lower than 1.5m/s;

A_r—tunnel clearance area (m^2).

7 Ventilation Calculation

7.1 General

7.1.1 Corresponding calculations shall be made for the highway tunnel ventilation design in accordance with the requirements at the stages of engineering feasibility study, preliminary design and construction drawing design.

***Background*:**
At the engineering feasibility study stage, rough calculations shall be made for the required air volume flow and design air velocity according to such conditions as the tunnel length, horizontal and vertical alignments and cross section at this stage. Besides, the preliminary analysis on the economy and rationality of ventilation system shall be conducted.

At the preliminary design stage, the comparison and selection of ventilation schemes shall be carried out and the ventilation system shall be designed preliminarily, namely to calculate the requested air pressure and volume, general specifications and quantity of fans based on the survey data of the tunnel ventilation design, and at the same time, to propose the design scheme for phased implementation of ventilation system and determine the ventilation system size.

For technically complex ventilation systems, such as systems combined withfull transverse ventilation, multiple vertical shafts (or inclined shafts) and jet fan sectional ventilation, numerical or physical simulation test is the common means for the research and analysis when it is difficult to determine the combined air pressures, air volume flow, sectional air velocity, air supply and exhaust air pressures, construction types of air inlets, air outlets, ducts, etc.

At the construction drawing design stage, the ventilation calculations and designs shall further improve the design results of preliminary design or technical design to determine the detail structures of ventilation system, precisely calculate the requested air pressure and volume, calculate various ventilation conditions (such as the single-tube bi-directional traffic in the near future and long-term double-tubeuni-directional traffic, phased installation of ventilation facilities and traffic volume change) after the tunnel comes into service and prepare the overall operation scheme for ventilation facilities.

7.1.2 In the ventilation system, the air volume flow provided by fans and piston effect of traffic shall meet the requirements for required air volume flow and overcoming ventilation resistance.

Background:
The fans mentioned in this Clause include jet fans and axial fans.

7.1.3 In the ventilation calculation of highway tunnel, the air may be deemed as incompressible fluid; the air flow in tunnel may be deemed as a steady flow that does not change with time and the vehicle running may also be deemed as a steady flow. At normal atmospheric pressure, the values of physical quantities of air may be referred to Table 7.1.3. Under other conditions, the ambient air density ρ may be calculated by formula (7.1.3):

Table 7.1.3 Physical quantities of air

Specific weight γ (N/m^3)	11.77
Density ρ_0 (kg/m^3)	1.20
Kinematic viscosity ν (m^2/s)	1.57×10^{-5}

$$\rho = \rho_0 \times \exp\left(-\frac{h}{29.28T}\right) \tag{7.1.3}$$

Where:

ρ—ambient air density at ventilation calculation point (kg/m^3);

ρ_0—ambient air density at normal atmospheric pressure (kg/m^3);

T—summer temperature at ventilation calculation point (K);

h—altitude above sea level at ventilation calculation point (m).

Background:
The ventilation speed ina tunnel and ventilation shaft is generally below 30.0m/s, so the compressibility of air may be neglected. The flow involved in ventilation calculation is complicated at the micro level, but may be regarded as a steady flow at the macro level, which is feasible in practical applications.

7.1.4 The values of on-way resistance coefficient and local resistance coefficient shall be determined based on the tunnel or duct's cross section hydraulic diameter and wall roughness, as well as the structure and shape of duct. When concrete walls are adopted, the common resistance coefficients may be obtained according to Table 7. 1. 4. The resistance coefficients of other materials, bent duct and variable cross section may be calculated or obtained according to Appendix A, Appendix B and Appendix C.

Table 7.1.4 Table of commonresistance coefficients

Resistance coefficient	Value
On-wayresistance coefficient λ_r	0.02
On-wayresistance coefficient of main duct(including shaft) λ_b, λ_e	0.022
On-wayresistance coefficient of connecting duct λ_e	0.025
Localresistance coefficient of tunnel entrance ζ_e	0.5
Localresistance coefficient of tunnel exit ζ_{ex}	1.0

***Background*:**

Theresistance coefficients in this Clause are based on concrete walls. Where walls are decorated with the materials with smooth surfaces, the resistance coefficients are usually determined by means of test or actual measurement at home and abroad.

7.2 Tunnel natural ventilation effect

7.2.1 The tunnel natural ventilation effect shall be determined according to the following principles:

1 For ventilation calculation, the natural ventilation effect shall be considered as a tunnel ventilation resistance; if it is confirmed that the air velocity in tunnel caused by natural wind is always consistent with the tunnel ventilation direction, the natural ventilation should be considered as a tunnel ventilation impetus.

2 The air velocity in tunnel caused by natural wind should be determined based on the meteorological survey data, tunnel length, longitudinal grade, etc.; where no relevant survey result is obtained, 2.0 ~ 3.0m/s may be taken as the value.

3 For the tunnels adopted with sectional longitudinal ventilation through ventilation shafts, the natural ventilation effect in each ventilation segment shall be analyzed and determined based on the actual conditions.

***Background*:**

1 The pressure difference caused by tunnel natural wind mainly consists of the difference in

atmospheric pressure between tunnel portals, pressure difference caused by temperature difference inside and outside tunnel and external wind pressure generated when the outside monsoon blows into the tunnel portal. In reality, the force and direction of such natural ventilation effect often change due to the time and natural air velocity and direction change. Therefore, from the perspective of safety, the natural wind is usually considered in the opposite direction of traffic in ventilation calculations, namely considered as a resistance. Sometimes, $\Delta p_m = 0$ may also be considered. However, if it is confirmed that the air velocity in tunnel caused by natural wind is always consistent with the tunnel ventilation direction, it should be considered as a tunnel ventilation impetus.

2 The air velocity in tunnel caused by natural wind refers to the air velocity in the tunnel generated under the effect of natural wind, instead of the natural air velocity in the atmosphere outside the tunnel. The force may be actually measured after the tunneling, but it is hard to be obtained at the design stage and is generally determined by experience currently.

3 For the tunnels adopted with sectional longitudinal ventilation through ventilation shafts, the air velocity in tunnel in each ventilation segment caused by natural wind is different due to the influence of ventilation shafts. Therefore, the natural ventilation effect in each ventilation segment shall be analyzed and determined according to the actual location of each section.

7.2.2 The natural ventilation effect shall be calculated by formula (7.2.2): If the natural ventilation effect is considered as a tunnel ventilation resistance, the formula (7.2.2) result shall be "+"; while if the natural ventilation effect is considered as a tunnel ventilation impetus, the formula (7.2.2) result shall be "−".

$$\Delta P_m = \pm\left(1 + \zeta_e + \lambda r \cdot \frac{L}{Dr}\right) \cdot \frac{\rho}{2} \cdot v_n^2 \qquad (7.2.2)$$

Where:

Δp_m—natural ventilation in tunnel (N/m^2);

v_n—air velocity in tunnel caused by natural wind (m/s), with the value according to Clause 7.2.1;

ζ_e—tunnel entrance local resistance coefficient, with the value according to Table 7.1.4;

λ_r—tunnel on-way resistance coefficient, with the value according to Table 7.1.4;

D_r—hydraulic diameter of tunnel cross section (m), $Dr = \frac{4 \times A_r}{C_r}$;

A_r—tunnel clearance area (m^2);

C_r—perimeter of tunnel cross section (m).

***Background*:**

The natural ventilation effect is proportional to the tunnel length and air velocity in tunnel caused by natural wind, as shown in Figure 7-1.

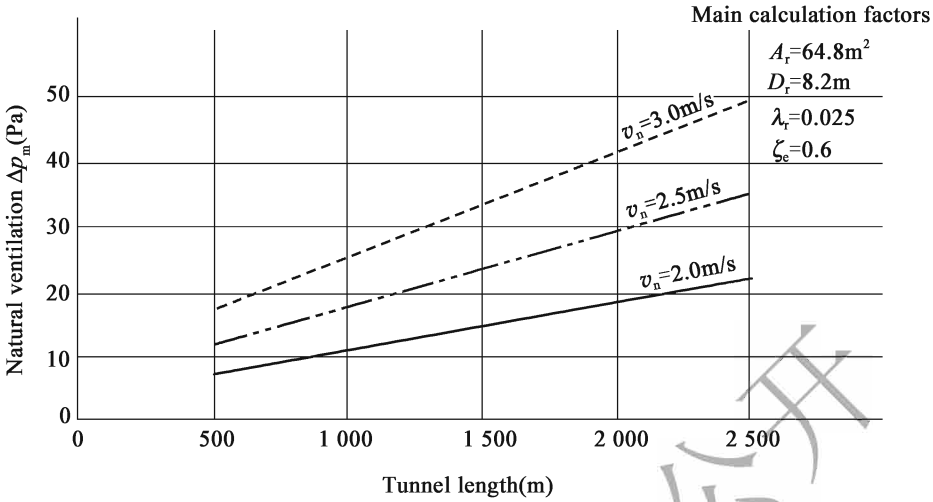


Figure 7-1 Relation between the natural ventilation Δp_m and tunnel length and air velocity in tunnel caused by natural wind v_n

7.3 Piston effect of traffic in tunnel

7.3.1 The piston effect of traffic in tunnel shall be determined according to the following principles:

1 Foruni-directional traffic, the piston effect of traffic in tunnel should be considered as an impetus; when the vehicle speed under working condition is lower than the design air velocity, the piston effect of traffic shall be considered as a resistance.

2 For bi-directional traffic, thepiston effect of traffic should be considered as a resistance.

3 Thepiston effect of traffic shall be calculated separately according to the vehicle speed under each working condition below the design speed.

Background:

1 In case ofuni-directional traffic, the piston effect of traffic in tunnel is considered as an impetus. The vehicle speed under working condition refers to the vehicle speed graded every 10km/h below the design speed. When the vehicle speed under working condition is below the design air velocity, the vehicle will become a local resistance to the in-tunnel airflow. In case of congested traffic or slow moving of vehicles, the piston effect of traffic is considered as a resistance. Otherwise, it may lead to the problem of inefficient ventilation.

2 In case of bi-directional traffic where thepiston wind generated by vehicles can't be completely

utilized, the piston effect of traffic is usually considered as a resistance in order to avoid the problem of inefficient ventilation.

3 Thepiston effect of traffic is related to the vehicle speed under working condition, and that caused by vehicle speeds under different conditions is different. In order to avoid the problem of inefficient or excessive ventilation, the piston effect of traffic shall be calculated separately according to the vehicle speed under each working condition below the design speed.

7.3.2 The piston effect of traffic in a single-tube bi-directional tunnel may be calculated by formula(7.3.2):

$$\Delta P_t = \frac{A_m}{A_r} \cdot \frac{\rho}{2} \cdot n_+ \cdot (v_{t(+)} - v_r)^2 - \frac{A_m}{A_r} \cdot \frac{\rho}{2} \cdot n_- \cdot (v_{t(-)} + v_r)^2 \qquad (7.3.2)$$

Where:

Δp_t—piston effect of traffic(N/m^2);

n_+—number of vehicles in tunnel in the same direction as v_r(veh.), $n_+ = \frac{N_+ \cdot L}{3600 \cdot v_{t(+)}}$;

n_-—number of vehicles in tunnel in the opposite direction to v_r(veh.), $n_- = \frac{N_- \cdot L}{3600 \cdot v_{t(-)}}$;

N_+—design PHV in tunnel in the same direction as v_r(veh./h);

N_-—design PHV in tunnel in the opposite direction to v_r(veh./h);

v_r—design air velocity in tunnel(m/s), $vr = \frac{Q_r}{A_r}$;

$v_{t(+)}$—vehicle speed under various conditions in the same direction as v_r(m/s);

$v_{t(-)}$—vehicle speed under various conditions in the opposite direction to v_r(m/s);

Q_r—design air volume flow of tunnel(m^3/s);

A_m—equivalent vehicle resistance area(m^2).

Background:

The direction of the tunnel design air velocity v_r is the design ventilation direction. For all formulas in this Clause, the direction of the tunnel design air velocity v_r is the forward direction. Special attention shall be paid to the determination of directions of n_+, n_- and $v_{t(+)}$, $v_{t(-)}$.

7.3.3 The piston effect of traffic in a uni-directional tunnel may be calculated by formula(7.3.3): Where $v_t > v_r$, Δp_t is "+"; where $v_t < v_r$, Δp_t is "−".

$$\Delta P_t = \pm \frac{A_m}{A_r} \cdot \frac{\rho}{2} \cdot n_C \cdot (v_t - v_r)^2 \qquad (7.3.3)$$

Where:

n_c—number of vehicles in tunnel(veh.), $n_C = \frac{N \cdot L}{3600 \cdot v_t}$;

v_t—vehicle speed under various conditions(m/s);

7.3.4 The equivalent vehicle resistance area may be calculated by formula (7.3.4-1):

$$A_m = (1 - r_1) \cdot Acs \cdot \xi c1 + r_1 \cdot A_{cl} \cdot \xi_{c2} \qquad (7.3.4\text{-}1)$$

Where:

A_{cs}—frontal projected area of small vehicle (m^2), may be 2.13m^2;

A_{cl}—frontal projected area of large vehicle (m^2), may be 5.37m^2;

r_1—ratio of large vehicles;

ε_{ci}—air drag coefficient of small or large vehicles in tunnel, calculated by formula (7.3.4-2);

$$\xi_{ci} = 0.0768 x_i + 0.35 \qquad (7.3.4\text{-}2)$$

x_i—vehicle blockage ratio of vehicle type i in tunnel space (%).

Background:

The large vehicles and small vehicles mentioned in this Clause are divided in accordance with *Traffic Engineering Manual* (edited chiefly by Liu Yicheng, published by China Communications Press, May 1998), among which the large vehicles include medium and heavy trucks, articulated trailers, monoblock and articulated buses; and small vehicles include jeeps, motorcycles, goods trucks with load ≤2t, minibuses ≤12 seats.

Due to various types of vehicles in tunnel, the average values of the frontal projected area A_c and air drag coefficient ε_c of vehicle groups are calculated. The values specified in this Clause are statistic values of several major types of vehicles. If possible, the air drag coefficient may be obtained through tests.

In accordance with *Automotive Application Engineer Manual* (edited chiefly by He Guangli, published by China Communications Press, February 1991), the frontal areas and coefficients of drag of hybrid vehicle types in China are as shown in Table 7-1 and Table 7-2.

Table 7-1 Frontal areas and coefficients of drag of passenger and commercial vehicles

Category	Passenger vehicle			Commercial vehicle			
Sub-category	Basic passenger vehicle	Multi-purpose /sports-utility vehicle	Cross passenger vehicle	Bus	Truck	Semi-articulated trailer	Combination vehicle
Frontal area	1.7 ~ 2.1	2.2 ~ 5.0	2.5 ~ 6.0	4.0 ~ 7.0	3.0 ~ 7.0	6.5 ~ 9.0	6.5 ~ 9.0
Air drag coefficient	0.25 ~ 0.41	0.30 ~ 0.51	0.35 ~ 0.51	0.50 ~ 0.80	0.60 ~ 1.00	0.60 ~ 1.00	0.70 ~ 1.10

Table 7-2 Frontal areas and coefficients of drag of commercial trucks

Type of combination vehicle	Frontal area A (m^2)	Air drag coefficient CD
Articulated semi-trailer combination (flat container)	6.5	0.7
Articulated semi-trailer combination (canvas top)	8.0	0.9

continued

Type of combination vehicle	Frontal area$A$(m^2)	Air drag coefficient CD
Articulated semi-trailer combination(van)	8.0	0.7
Articulated semi-trailer combination(with box container)	9.0	1.1
Lorry-monoblock		0.85

According to relevant studies, theresistance coefficient of vehicle in tunnel is related to the vehicle blockage ratio of the vehicle in the tunnel driving space (namely the percentage of the vehicle frontal projected area in the sectional area of the tunnel driving space). In order to reflect the piston effect of traffic in the calculation of longitudinal ventilation, the vehicle blockage ratio is adopted to calculate the resistance coefficient of vehicle herein. The vehicle blockage ratio is the ratio of the frontal projected area of large and small vehicles to the clearance area of tunnel driving space.

7.4 Tunnel ventilation resistance

7.4.1 The ventilation resistance in tunnel shall be calculated by formula (7.4.1-1) ~ formula (7.4.1-3):

$$\Delta p_r = \Delta p_\lambda + \sum \Delta p_{\zeta i} \tag{7.4.1-1}$$

$$\Delta P_\lambda = \left(\lambda r \cdot \frac{L}{Dr}\right) \cdot \frac{\rho}{2} \cdot v_r^2 \tag{7.4.1-2}$$

$$\sum \Delta P_{\zeta i} = \zeta_i \cdot \frac{\rho}{2} \cdot v_r^2 \tag{7.4.1-3}$$

Where:

Δp_r—ventilation resistance in tunnel(N/m^2);

Δp_λ—on-way resistance in tunnel(N/m^2);

$\Delta p_{\zeta i}$—local resistance in tunnel(N/m^2);

ζ_i—tunnel local resistance coefficient, with the value according to Table 7.1.4, Appendix B and Appendix C.

7.5 Longitudinal ventilation with full jet stream

7.5.1 The pattern of longitudinal ventilation with full jet stream is as shown in Figure 7.5.1.

7.5.2 The pressure balance in tunnel shall satisfy formula(7.5.2):

$$\Delta P_r + \Delta P_m = \Delta P_t + \sum \Delta P_j \tag{7.5.2}$$

Where:

$\sum \Delta p_j$—total pressure rise of jet fans(N/m^2).

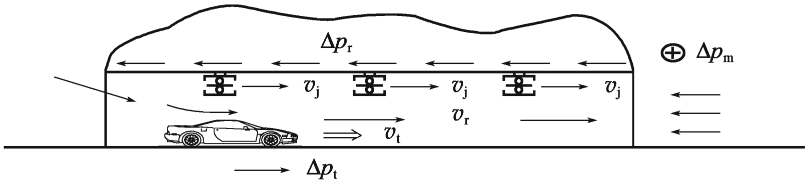


Figure 7.5.1 Pattern oflongitudinal ventilation with full jet stream

7.5.3 The pressure rise and quantity of jet fans demanded shall be calculated according to the following requirements:

1 The pressure rise per jet fan shall be calculated by formula(7.5.3-1):

$$\Delta p_j = \rho \cdot v_j^2 \cdot \frac{A_j}{A_r} \cdot \left(1 - \frac{v_r}{v_j}\right) \cdot \eta \qquad (7.5.3\text{-}1)$$

Where:

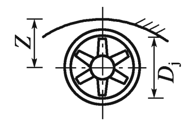
Δp_j—pressure rise per jet fan(N/m^2);

v_j—outlet air velocity of jet fan(m/s);

A_j—outlet area of jet fan(m^2);

η—efficiency due to resistance loss at jet fan location. Where only one jet fan is arranged in the same tunnel section, the value may be according to Table 7.5.3; where two or more jet fans are arranged in the same tunnel section, 0.7 may be taken as the efficiency due to resistance loss at the jet fan location η.

Table 7.5.3 Efficiency due to resistance loss at a jet fan location η

Z/D_j	1.5	1.0	0.7	Diagram
η	0.91	0.87	0.85	

Note: D_j in the table refers to the inner diameter of the jet fan.

2 Under the condition that the tunnel design air velocity v_r is satisfied, the quantity of jet fans may be calculated by formula(7.5.3-2):

$$i = \frac{\Delta p_r + \Delta p_m - \Delta p_t}{\Delta p_j} \qquad (7.5.3\text{-}2)$$

Where:

i—quantity of jet fans needed(set).

3 The standby jet fans should be jet fans of the same model. Where 1 ~ 6 groups of jet fans are needed after calculation, one group may be prepared for standby; where over 6 groups

of jet fans are needed after calculation, 15% of the quantity needed may be prepared for standby.

Background:

In the majority of tunnels in China, the jet fans are hung from the arch crown. However, there are also fans set on side walls near the abut, in which case theresistance loss of pressure rise of fan and the influence of jet stream speed on traffic safety shall be fully discussed. From the perspectives of equipment overhauling and fire prevention, a certain standby quantity of jet fans set in tunnel shall be considered.

7.6 Longitudinal ventilation with Saccardo nozzle

7.6.1 The longitudinal ventilation with Saccardo nozzle shall be designed in accordance with the following provisions:

1 The longitudinal ventilation with Saccardo nozzle should be used inuni-directional tunnels.

2 Comprehensive comparisons from the technical and economic aspects shall be made for the air inlet structures, fan room structures and duct connection methods.

3 The jet stream direction at air inlet should be consistent with the tunnel axial direction.

4 Guiding devices should be set up atbent duct.

7.6.2 The pattern of longitudinal ventilation with Saccardo nozzle may be as shown in Figure 7.6.2.

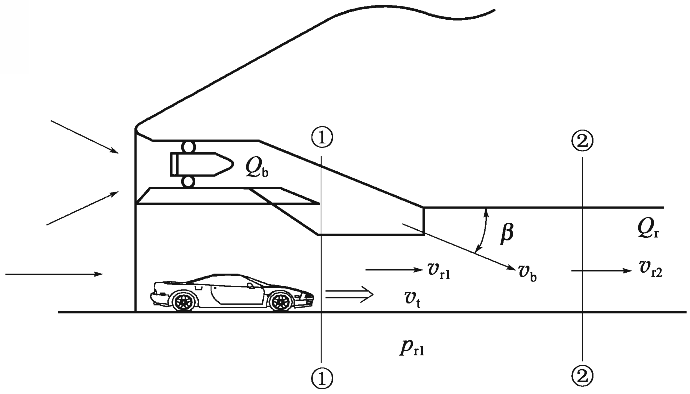


Figure 7.6.2 Pattern of longitudinal ventilation with Saccardo nozzle

7.6.3 The pressure rise at air inlet of ventilation fan may be calculated by formula (7.6.3):

$$\Delta p_b = 2 \cdot \frac{Q_b}{Q_r} \cdot \left(\frac{K_b \cdot v_b \cdot \cos\beta}{v_r} - 2 + \frac{Q_b}{Q_r}\right) \cdot \frac{\rho}{2} \cdot v_r^2 \tag{7.6.3}$$

Where:

Δp_b—pressure rise at air inlet of air supply fan (N/m^2);

Q_r—design air volume flow in tunnel (m^3/s), generally $Q_r = Q_{req}$;

Q_{req}—required air volume flow in tunnel (m^3/s);

Q_b—air volume flow from air inlet, namely air volume flow of the air supply fan (m^3/s);

v_b—jet speed at air inlet, generally 20.0 ~ 30.0m/s;

β—angle between jet stream direction and the tunnel axis (°);

K_b—momentum coefficient of pressure rise at air inlet, $K_b = 1.0$.

7.6.4 The air inlet area A_b may be calculated by formula (7.6.4), and it should not be greater than 12.0m^2 for two-lane tunnels.

$$A_b = \frac{Q_b}{v_b} \tag{7.6.4}$$

7.6.5 The air volume flow of air supply fan may be calculated by formula (7.6.5-1) and formula (7.6.5-2) and the total pressure of air supply fan may be calculated by formula (7.6.5-3):

$$Q_b = \frac{Q_r}{2} \cdot \left(\sqrt{a^2 + \frac{4\Delta p_b}{\rho \cdot v_r^2}} - a\right) \tag{7.6.5-1}$$

$$a = \frac{K_b \cdot v_b \cdot \cos\beta}{v_r} - 2 \tag{7.6.5-2}$$

$$p_{tot} = \left(\frac{\rho}{2} \cdot v_b^2 + \Delta p_d\right) \times 1.1 \tag{7.6.5-3}$$

Where:

p_{tot}—design total pressure of air supply fan (N/m^2);

Δp_d—total pressure loss in duct, air inlet, etc. (N/m^2).

Background:

In the longitudinal ventilation with Saccardo nozzle, the axial fans are arranged near tunnel portals, with the jet steam direction consistent with the traffic direction. The air pressure generated together with thepiston effect of traffic will overcome the tunnel ventilation resistance and natural wind resistance. By the conservation of momentum, the momentum formulas for such two sections as shown in Figure 7.6.2 are as follows:

$$-A_r \cdot \Delta p_b = \rho \cdot Q_r \cdot v_{r2} - [\rho \cdot (Q_r - Q_b) \cdot v_{r1} + K_b \cdot \rho \cdot Q_b \cdot v_b \cdot \cos\beta] \tag{7-1}$$

$$v_{r1} = \frac{Q_r - Q_b}{A_r}; \quad v_{r2} = \frac{Q_r}{A_r} \tag{7-2}$$

The working principle of longitudinal ventilation with Saccardo nozzle is basically the same as that of jet fan, which belongs to the same type. In such mode, large high-speed air volume flow will exist in the tunnel, so it is generally applicable to uni-directional tunnels. It has such advantages as convenient centralized control and management and significant pressure rising effect. At present, no tunnel is adopted with such mode in China, so foreign experience and standards are taken as references for the ventilation parameters adopted herein.

As for the momentum coefficient K_b of pressure rise at air inlet, the structures and construction costs of supply ducts and air inlets must be taken into overall consideration to ensure $K_b = 1.0$ as much as possible. Figure 7-2 shows the relation between the pressure rise increment at air inlet and momentum coefficient K_b of pressure rise at air inlet. The figure is the test result of Civil Works Research Institute of the Ministry of Construction of Japan.

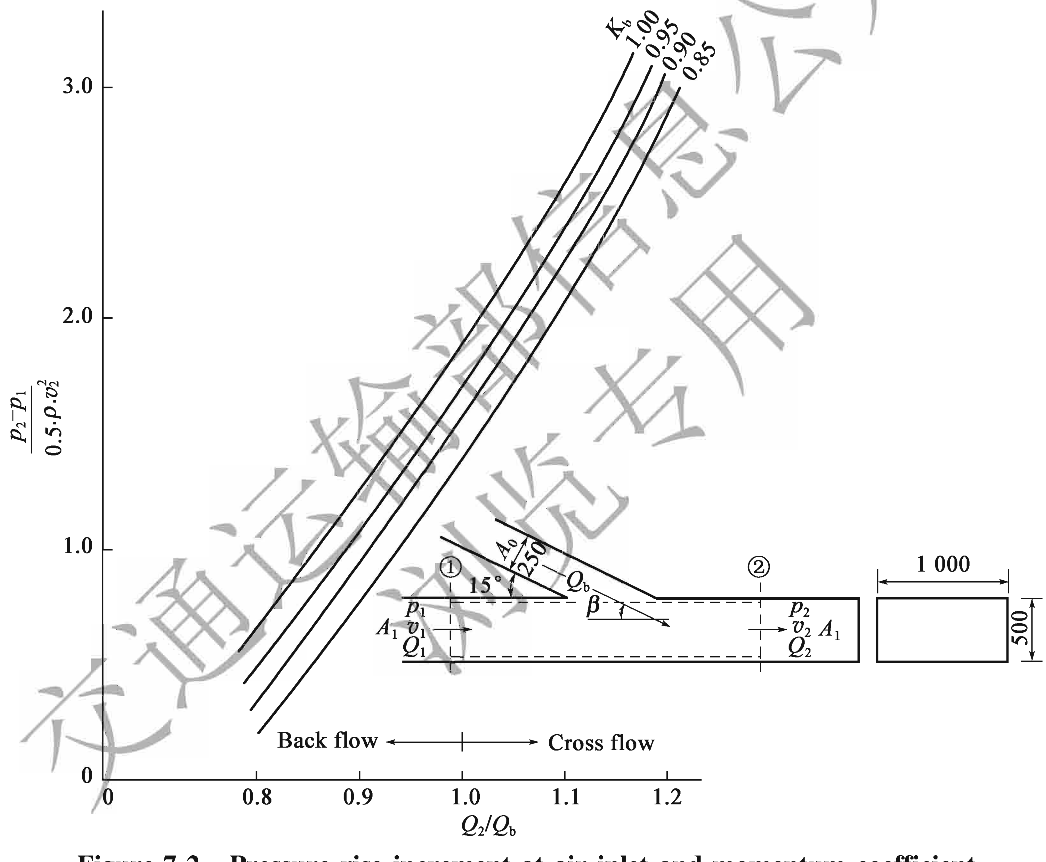


Figure 7-2　Pressure rise increment at air inlet and momentum coefficient K_b of pressure rise at air inlet (unit: cm)

7.7　Longitudinal ventilation with exhaust shaft

7.7.1　Where the longitudinal ventilation with exhaust shaft is applied in a uni-directional tunnel, the merging or diverging longitudinal ventilation with exhaust shaft may be adopted and the ventilation shaft should be set up at the tunnel exit side.

7.7.2 Where the longitudinal ventilation with exhaust shaft is applied in a bi-directional tunnel, the merging longitudinal ventilation with exhaust shaft should be adopted and the ventilation shaft should be set up at the middle of the longitudinal length of the tunnel.

Background:

7.7.1 ~ 7.7.2 Thelongitudinal ventilation with exhaust shaft makes use of the negative pressure generated at the shaft bottom to realize ventilation. Such ventilation mode is generally applicable to bi-directional tunnels; where a uni-directional tunnel has strict environment requirements around its exit, namely that no polluted air is allowed to be blown out from the tunnel (exit), such ventilation mode can also be adopted, but in the short zone of tunnel (exit side), the airflow is in the opposite direction of traffic direction and the overall design wind direction of tunnel, which will cause relatively large pressure loss and may also make flow disturbance. Special attention must be paid to these aspects for design calculation. From the perspective of environmental protection, it is theoretically feasible that the discharge amount of in-tunnel polluted air is zero, but it needs relatively large ventilation shaft exhaust power, resulting in high power consumption; on the other hand, the vehicle traffic flow itself will bring out a part of air volume flow. Therefore, it is very difficult to realize zero polluted air volume flow at the exit, which must be taken into account in design.

7.7.3 The merging longitudinal ventilation with exhaust shaft of bi-directional tunnels shall be designed in accordance with the following provisions:

1 The pressure mode of merginglongitudinal ventilation with exhaust shaft of bi-directional tunnels may be as shown in Figure 7.7.3.

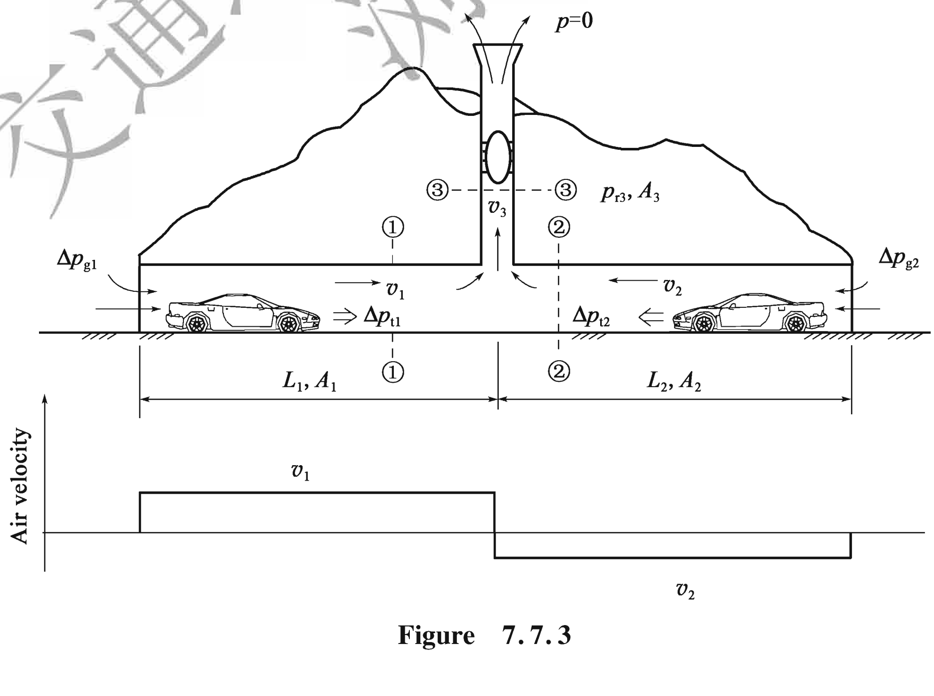


Figure 7.7.3

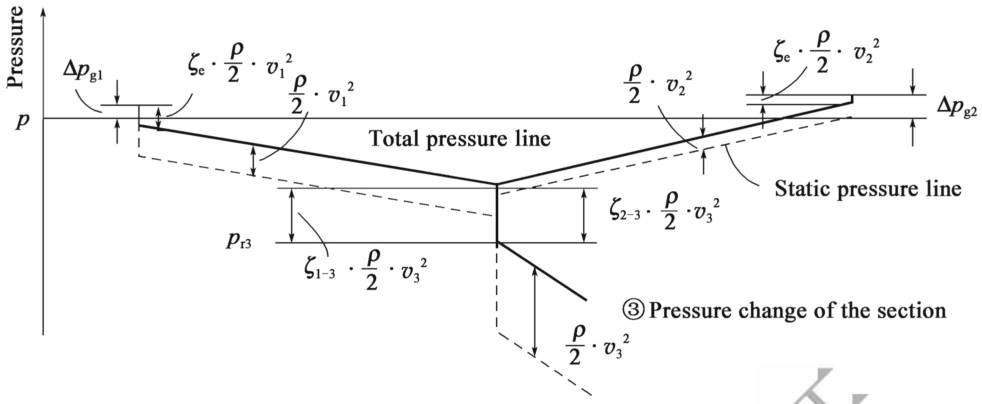


Figure 7.7.3 Pressure mode of merginglongitudinal ventilation with exhaust shaft

2 The total pressure after combination at ventilation shaft bottom may be calculated by formula(7.7.3-1):

$$
\begin{aligned}
p_{tot3} &= \Delta p_{g1} + \Delta p_{t1} - \left(\zeta_e + \lambda_r \cdot \frac{L_1}{D_r}\right) \cdot \frac{\rho}{2} \cdot v_1^2 - \zeta_{1-3} \cdot \frac{\rho}{2} \cdot v_3^2 \\
&= \Delta p_{g2} + \Delta p_{t2} - \left(\zeta_e + \lambda_r \cdot \frac{L_2}{D_r}\right) \cdot \frac{\rho}{2} \cdot v_2^2 - \zeta_{2-3} \cdot \frac{\rho}{2} \cdot v_3^2
\end{aligned}
\tag{7.7.3-1}
$$

$$\Delta p_{t1} = \frac{A_m}{A_r} \cdot \frac{\rho}{2} \cdot [n_{+1} \cdot (v_t - v_1)^2 - n_{-1} \cdot (v_t + v_1)^2] \tag{7.7.3-2}$$

$$\Delta p_{t2} = \frac{A_m}{A_r} \cdot \frac{\rho}{2} \cdot [n_{-2} \cdot (v_t - v_2)^2 - n_{+2} \cdot (v_t + v_2)^2] \tag{7.7.3-3}$$

Where:

p_{tot3}—total pressure at ventilation shaft bottom(N/m^2);

Δp_{g1}—meteorological pressure difference between tunnel portal and ventilation shaft outlet(N/m^2) in Zone I, "+" where the natural wind is in the same direction as the tunnel ventilation direction;

L_1—length of Zone I(m);

ζ_{1-3}—loss coefficient in Zone I by taking the air velocity in ventilation shaft as the base;

Δp_{g2}—meteorological pressure difference between tunnel portal and ventilation shaft outlet(N/m^2) in Zone II, "+" where the natural wind is in the same direction as the tunnel ventilation direction;

L_2—length of Zone II(m);

ζ_{2-3}—loss coefficient in Zone II by taking the air velocity in ventilation shaft as the base;

v_1—average air velocity of Section ①-① in Zone I(m/s);

v_2—average air velocity of Section ②-② in Zone II(m/s);

v_3—average air velocity of Section ③-③ in ventilation shaft(m/s);

Δp_{t1}—piston effect of traffic in Zone I(N/m^2);

n_{+1}—number of vehicles in Zone I driving from Zone I to Zone II(veh.);

n_{-1}—number of vehicles in Zone I driving from Zone II to Zone I(veh.);

Δp_{t2}—piston effect of traffic in Zone II(N/m^2);

n_{+2}—number of vehicles in Zone II driving from Zone I to Zone II(veh.);

n_{-2}—number of vehicles in Zone II driving from Zone II to Zone I(veh.).

Background:

The Δp_g in Figure 7.7.3 of this Clause is the meteorological pressure difference between portal and ventilation shaft outlet, taking the ventilation shaft outlet as the base. The Δp_g generates long-term pressure boosting effect, which is a ventilation thrust (different from the natural wind resistance Δp_m).

7.7.4 The merging longitudinal ventilation with exhaust shaft of uni-directional tunnels may be calculated in accordance with the following requirements:

1 The pressure mode of merginglongitudinal ventilation with exhaust shaft of uni-directional tunnels is as shown in Figure 7.7.3. The driving direction in tunnel exit zone is opposite to the tunnel ventilation direction.

2 The total pressure after combination at ventilation shaft bottom may be calculated by formula(7.7.3-1), and thepiston effect of traffic in Zone I and Zone II may be calculated by formula(7.3.2).

Background:

Inuni-directional tunnels, the airflow in tunnel short zone(exit side) under merging pressure mode flows in the opposite direction to the tunnel overall design wind direction, and is also against the driving direction. It must be taken into full account in the design calculation in order to avoid unbalanced or insufficient ventilation on left and right sides of ventilation shaft bottom mainly affected by traffic conditions.

7.7.5 The diverging longitudinal ventilation with exhaust shaft of uni-directional tunnels may be calculated in accordance with the following requirements:

1 The pressure mode of diverginglongitudinal ventilation with exhaust shaft may be as shown in Figure 7.7.5.

2 The total pressure at the end of Zone I of tunnel(total pressure before branching) may be calculated by formula(7.7.5-1):

$$p_{tot1} = \Delta p_{g1} + \Delta p_{t1} - \left(\zeta_e + \lambda_r \cdot \frac{L_1}{D_r}\right) \cdot \frac{\rho}{2} \cdot v_1^2 \qquad (7.7.5\text{-}1)$$

Where:

p_{tot1}—total pressure at the end of Zone I(N/m^2).

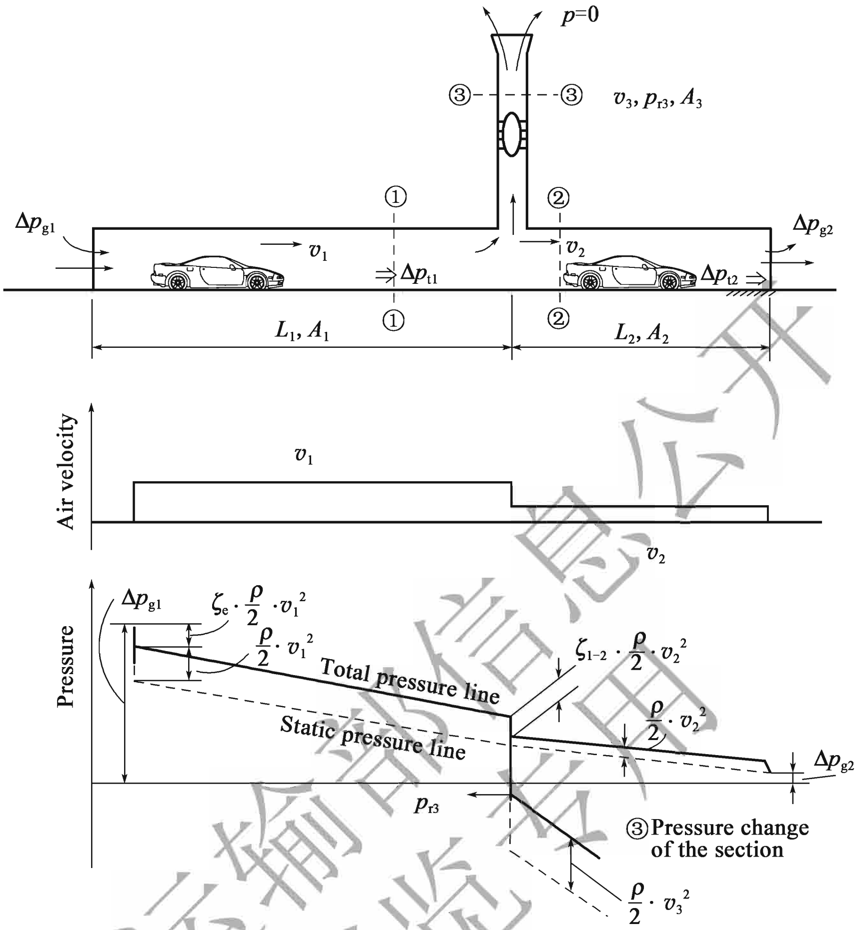


Figure 7.7.5 Pressure mode ofdiverging longitudinal ventilation with exhaust shaft

3 The total pressure at the start of Zone II of tunnel(total pressure after branching) may be calculated by formula(7.7.5-2):

$$p_{tot2} = \Delta p_{tot1} - \zeta_{1-2} \cdot \frac{\rho}{2} \cdot v_1^2 \qquad (7.7.5\text{-}2)$$

Where:

p_{tot2}—total pressure at the start of Zone II(N/m^2);

ζ_{1-3}—main steam branching loss coefficient of diverging duct, with the value according to Appendix C.

4 The total pressure at the end(exit) of Zone II of tunnel may be calculated by formula (7.7.5-3):

$$\Delta p_{g2} + \frac{\rho}{2} \cdot v_2^2 = p_{tot2} - \lambda_r \cdot \frac{L_2}{D_r} \cdot \frac{\rho}{2} \cdot v_2^2 + \Delta p_{t2} \qquad (7.7.5\text{-}3)$$

5　The total pressure at ventilation shaft bottom may be calculated by formula(7.7.5-4):

$$p_{tot3} = \Delta p_{tot1} - \zeta_{1-3} \cdot \frac{\rho}{2} \cdot v_1^2 \quad (7.7.5\text{-}4)$$

Where:

p_{tot3}—total pressure at ventilation shaft bottom(N/m^2);

ζ_{1-3}—branch stream branching loss coefficient of diverging duct, with the value according to Appendix C.

7.7.6　The longitudinal ventilation with exhaust shaft should be combined with jet fans to form a combined ventilation mode. The pressure balance of such combined ventilation mode shall meet formula(7.7.6):

$$\Delta p_e + \Delta p_j = \Delta p_r - \Delta p_t + \Delta p_m \quad (7.7.6)$$

Background:

In the pressure mode oflongitudinal ventilation with exhaust shaft, unbalanced or insufficient ventilation will occur on left and right sides of ventilation shaft bottom mainly affected by traffic conditions or natural wind. Considering the construction cost and operating electricity cost, the exhaust air volume flow shall not be too large.

One of solutions for above problems is the ventilation mode combined with jet fans, which can adjust the balance of air volume flow and air pressure in zones on both sides of ventilation shaft, so as to avoid the insufficient ventilation in Zone I and Zone II. Meanwhile, the exhaust system in longitudinal ventilation with exhaust shaft has a very weak pressure rising effect, which is usually difficult to be in balance with the pressure required by tunnel($\Delta p_r - \Delta p_t + \Delta p_m$). Therefore, jet fans with relatively significant pressure rising effect are always combined to solve the problem of insufficient pressure rising effect.

Another solution is to set up local wind shields at the tunnel arch crown to adjust the air pressure by increasing the ventilation resistance in a zone, so as to meet the balance of air volume flow and air pressure in two zones.

There are many types of wind screens as shown in Figure 7-3. Among them, Type A is usually adopted. Where more than 3 wind screens are set up, the value of loss coefficient ζ_j of each wind shield is stable. Where Type A is adopted, the relation between ζ_j and the spacing and size are as shown in Figure 7-4.

7.7.7　In ventilation calculation, repeated trials shall be carried out for corresponding required air volume flow, design air volume flow and air velocity of various schemes specific to different locations of ventilation shafts and jet fans, so as to determine a reasonable on-way pressure distribution.

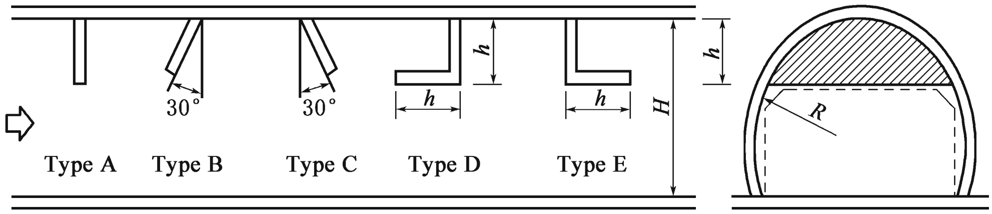


Figure 7-3 Types of wind shield

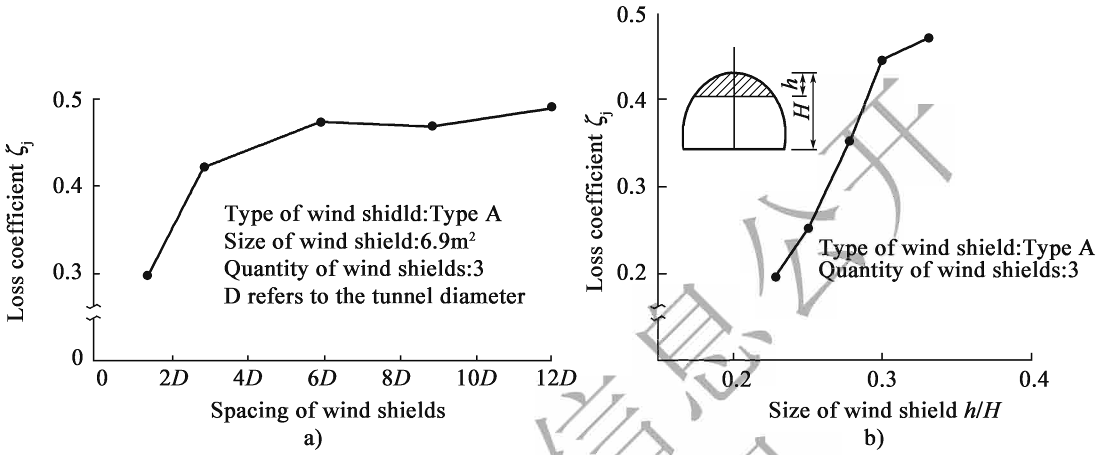


Figure 7-4 Influence of wind shield spacing and size on loss coefficient

7.7.8 The design air pressure of exhaust fan may be calculated by formula(7.7.8):

$$p_{tot} = 1.1 \times (p_{tot3} + \Delta p_d) \tag{7.7.8}$$

Where:

p_{tot}—design total pressure of exhaust fan(N/m^2);

Δp_d—total pressure loss in ventilation shaft and connecting duct(N/m^2).

Background:

The air volume flow, air velocity and air pressure in each zone may be determined based on the pressure mode, balance method and relevant loss coefficient as shown in Clause 7.7.3 or Clause 7.7.5, the total pressure required by fans can be obtained after the total pressure loss from the air outlet in tunnel to the ventilation shaft outlet (including connecting duct and ventilation shaft's wall resistance loss, curve loss and steel mesh ventilation door loss, etc.) and a certain air pressure margin are taken into consideration.

7.8 Longitudinal ventilation with supply and exhaust shafts

7.8.1 The design for longitudinal ventilation with supply and exhaust shafts shall be in accordance with the following provisions:

1 Thelongitudinal ventilation with supply and exhaust shafts should be applicable to uni-directional tunnels; tunnels with single-tube bi-directional traffic in the near future and long-term double-tube uni-directional traffic may be adopted with longitudinal ventilation with supply and exhaust shafts.

2 The maximum design air velocity in the tunnel should not be greater than 8.0m/s.

3 In design, thereverse flow in a short duct shall be prevented and the length of a short duct shall not be smaller than 50m.

4 A certain short-ductbypass flow air velocity shall be considered in the design; the air volume flow of a short-duct bypass flow and its pollution concentration shall be taken into full consideration in the calculation of air supply volume.

***Background*:**
In thelongitudinal ventilation with supply and exhaust shafts, the polluted air in tunnel is exhausted through exhaust shafts and fresh air is blown in through air supply shafts, so as to exhaust polluted air and blow in fresh air at the same time, which is applicable to extra-long highway tunnel ventilation.

1 For the tunnels constructed by stages and for long-termuni-directional traffic, the longitudinal ventilation with supply and exhaust shafts may be adopted. The ventilation facilities are calculated and equipped respectively based on the corresponding double-tube uni-directional traffic situation of long-term traffic volume and single-tube bi-directional traffic situation of near-term traffic volume. The ventilation mode also satisfies the bi-directional traffic of small near-term traffic volume, which is very economical.

2 Where thelongitudinal ventilation with supply and exhaust shafts is adopted, the installed power of ventilation facilities increases with the tunnel design air velocity. At the same time, from the perspective of piston effect of traffic, a vehicle will become local resistance of airflow in tunnel when the tunnel design air velocity is greater than the vehicle speed under working condition, in which case the piston effect of traffic can't be utilized. Where the design air velocity is too small, the ventilation zones will be increased, hence to increase the quantities of ducts, ventilation shafts and fans. Generally, it is economical and reasonable to set the tunnel design air velocity within 6.0 ~ 8.0m/s.

3 In order to avoid such problems asreverse flow, shortcut and pollution of airflow in short ducts between air inlets and air outlets, the length of short duct must be reasonable. The longer the short duct length, the higher the pollution concentration, and this zone has no fresh air supply, so

the short duct between air inlets and air outlets should not be too long from this sense; however, from the aspect of reverse flow prevention, the fresh air blown in through air inlets shall be avoided to be exhausted through air outlets, which will affect the ventilation efficiency, so the short duct shall not be too short. Therefore, it shall be comprehensively analyzed to determine a reasonable value. According to the engineering practice at home and abroad, generally, it is reasonable to set the length of a short duct to within 50 ~ 60m.

4 In order to avoid such problems asreverse flow and shortcut in short ducts between air inlets and air outlets, a certain bypass flow air velocity shall be provided. The air supply volume shall be calculated and determined based on sufficient estimate of the air volume flow from ventilation shaft bottom flowing from air outlets and short ducts and flowing into the end section of air inlets and its pollution concentration.

7.8.2 The pressure mode of longitudinal ventilation with supply and exhaust shafts may be as shown in Figure 7.8.2-1 and Figure 7.8.2-2. The pressure rise at air outlet may be calculated by formula(7.8.2-1) and the pressure rise at air inlet may be calculated by formula(7.8.2-2):

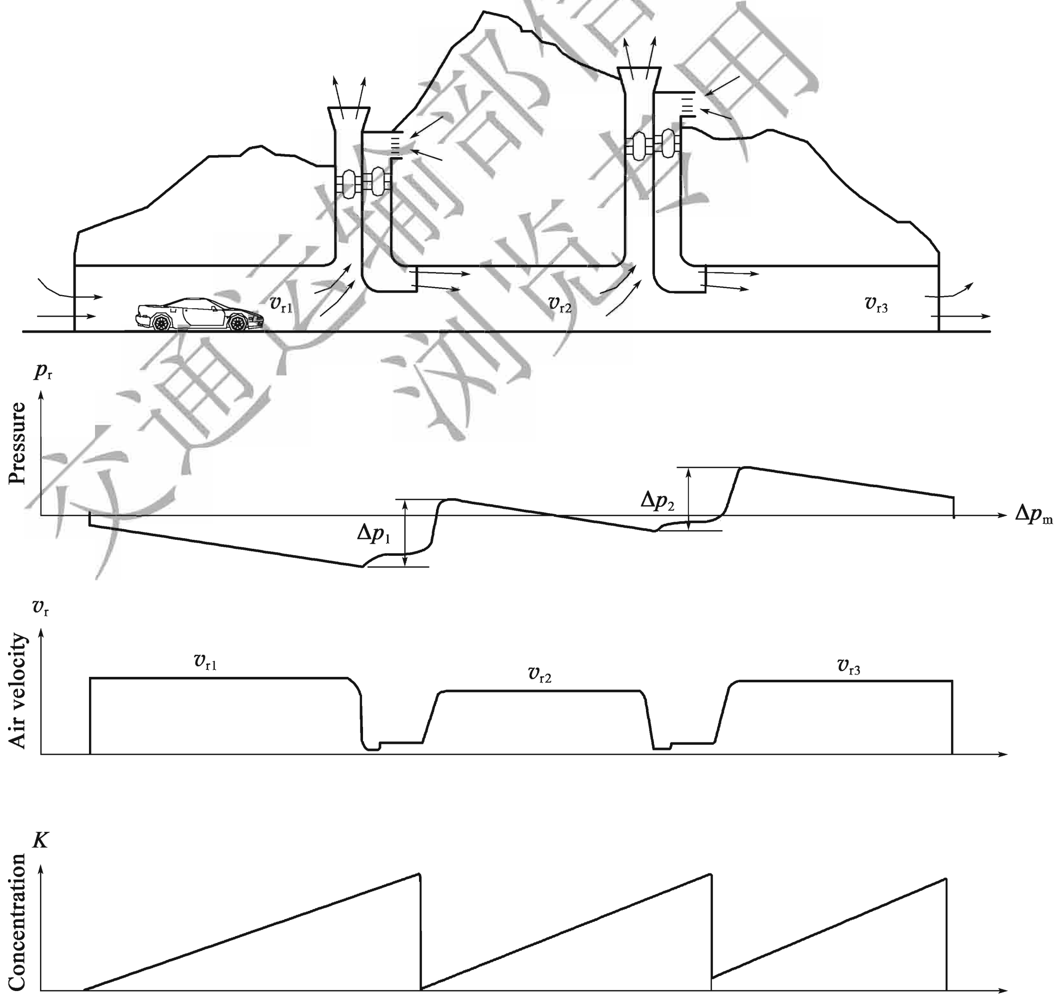


Figure 7.8.2-1 Air velocity, pressure and pollution concentration in tunnel

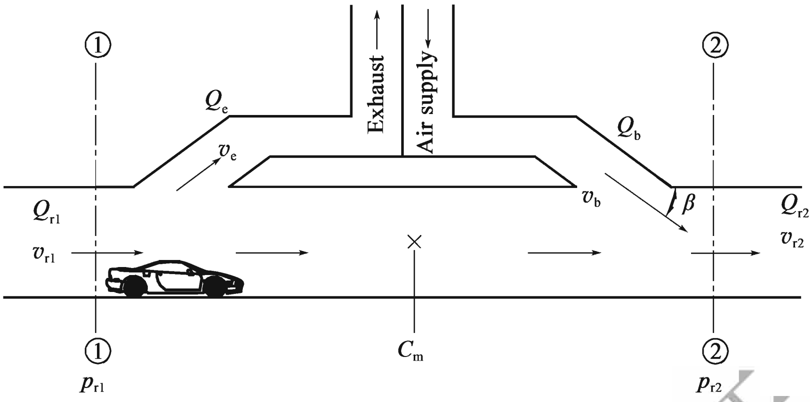


Figure 7.8.2-2 Pattern oflongitudinal ventilation with supply and exhaust shafts

$$\Delta p_e = 2 \cdot \frac{Q_e}{Q_{r1}}\left[\left(2 - \frac{v_e}{v_{r1}}\cos\alpha\right) - \frac{Q_e}{Q_{r1}}\right] \cdot \frac{\rho}{2} \cdot v_{r1}^2 \qquad (7.8.2\text{-}1)$$

$$\Delta p_b = 2 \cdot \frac{Q_b}{Q_{r2}}\left[\left(\frac{v_b}{v_{r2}}\cos\beta - 2\right) + \frac{Q_b}{Q_{r2}}\right] \cdot \frac{\rho}{2} \cdot v_{r2}^2 \qquad (7.8.2\text{-}2)$$

Where:

Δp_e—pressure rise at air outlet(N/m^2);

Δp_b—pressure rise at air inlet(N/m^2);

Q_{r1}—design air volume flow in Zone I(m^3/s);

v_{r1}—design air velocity in Zone I(m/s), $v_{r1} = \frac{Q_{r1}}{A_r}$;

Q_{r2}—design air volume flow in Zone II(m^3/s), $Q_{r2} = Q_b - Q_e + Q_{r1}$;

v_{r2}—design air velocity in Zone II(m/s), $v_{r2} = \frac{Q_{r2}}{A_r}$;

Q_e—exhaust air volume flow(m^3/s);

v_e—air outlet corresponding to Q_e(m/s).

Background:

With consideration to the pattern as shown in Figure 7-5, by applying theconservation of momentum of fluid mechanics on the control volume respectively taken from the air outlet and air inlet zones, there are the following relations:

$$A_r(p_{r2} - p_{r1}) = \rho \cdot Q_{r1} \cdot v_{r1} - (\rho \cdot Q_{r2} \cdot v_{r2} + \rho \cdot K_e \cdot Q_e \cdot v_e) \qquad (7\text{-}3)$$

$$A_r(p_{r4} - p_{r3}) = \rho \cdot Q_{r4} \cdot v_{r4} - (\rho \cdot Q_{r3} \cdot v_{r3} + \rho \cdot K_b \cdot Q_b \cdot v_b \cdot \cos\beta) \qquad (7\text{-}4)$$

The pressure rise Δp_e at air outlet and the pressure rise Δp_b at air inlet may be obtained by mathematical derivation respectively.

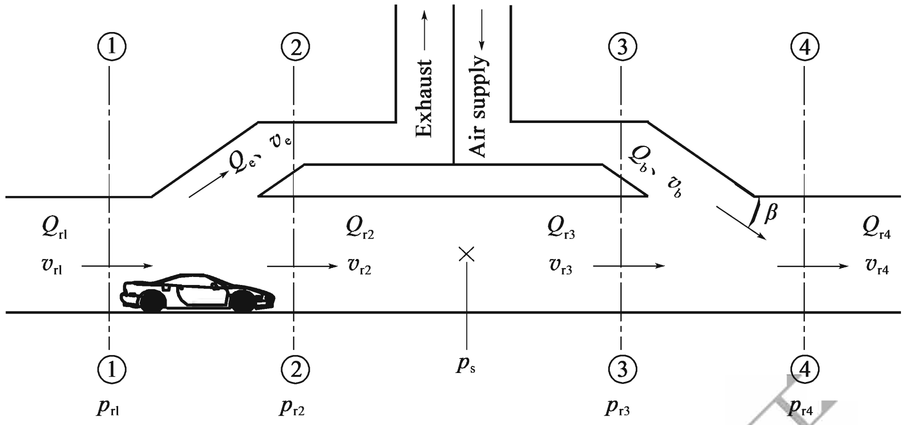


Figure 7-5 Pattern of ventilation shaft air inlet and air outlet

A lot of calculation results and some model test results show that if the tunnel design air velocity v_r is within 4.0 ~ 7.0m/s, the pressure rise at air outlet is much smaller than that at the air inlet. Therefore, the pressure rising effect mainly depends on air inlets. Generally, the pressure rise calculation is simplified to (assuming the design air velocity on both ends of ventilation shaft are the same and both are v_r):

$$\Delta p_b = 2 \cdot \frac{Q_b}{Q_r}\left[\left(\frac{v_b}{v_r}\cos\beta - 2\right) + \frac{Q_b}{Q_r}\right] \cdot \frac{\rho}{2} \cdot v_r^2 \qquad (7\text{-}5)$$

7.8.3 The design for longitudinal ventilation with supply and exhaust shafts may follow the principles below:

1 The tunnel air concentration C may be expressed by the ratio of required air volume flow to design air volume flow. The concentration C_2 at ventilation shaft air outlet may be calculated by formula (7.8.3-1); the equivalent fresh air volume flow Q_{sf} in the air flow at ventilation shaft bottom may be calculated by formula (7.8.3-2); the concentration C_3 inside the tunnel exit may be calculated by formula (7.8.3-3); and the air supply volume Q_b and exhaust volume Q_e may be calculated by formula (7.8.3-4):

$$C_2 = \frac{Q_{req1}}{Q_{r1}} \qquad (7.8.3\text{-}1)$$

$$Q_{sf} = Q_{r1} - Q_e - Q_{req1} + \frac{Q_e \cdot Q_{req1}}{Q_{r1}} \qquad (7.8.3\text{-}2)$$

$$C_3 = \frac{Q_{req2}}{Q_{r1} - Q_e - Q_{req1} + \frac{Q_e \cdot Q_{req1}}{Q_{r1}} + Q_b} \qquad (7.8.3\text{-}3)$$

$$Q_b = Q_{req} - Q_{r1} + Q_e \cdot \left(\frac{Q_{r1} - Q_{req1}}{Q_{r1}}\right) \qquad (7.8.3\text{-}4)$$

Where:

Q_{req1}—required air volume flow in Zone I of tunnel (m^3/s);

Q_{req2}—required air volume flow in Zone II of tunnel(m^3/s).

2 The conditions as shown in formula(7.8.3-5) and formula(7.8.3-6) shall be met to avoid thereverse flow in the short duct between air outlets and air inlets:

$$\frac{Q_e}{Q_{r1}} \leqslant 1.0 \quad (7.8.3\text{-}5)$$

$$\frac{Q_b}{Q_{r2}} \leqslant 1.0 \quad (7.8.3\text{-}6)$$

3 The design concentration shall meet the conditions as shown in formula(7.8.3-7) and formula(7.8.3-8):

$$0.9 \leqslant C_2 \leqslant 1.0 \quad (7.8.3\text{-}7)$$

$$0.9 \leqslant C_3 \leqslant 1.0 \quad (7.8.3\text{-}8)$$

4 The pressure in tunnel shall meet the condition as shown in formula(7.8.3-9):

$$\Delta p_b + \Delta p_e \geqslant \Delta p_r - \Delta p_t + \Delta p_m \quad (7.8.3\text{-}9)$$

Background:

Where thelongitudinal ventilation with supply and exhaust shafts is adopted, the concentration of exhaust gas along the whole tunnel is that: it nearly rises linearly from tunnel entrance and reaches at the maximum value at the bottom of ventilation shaft, drops rapidly after air inlet, and after that, it nearly rises linearly again. If there are several ventilation shafts, the above trends will be repeated. Therefore, theoretically, there is no limit to tunnel length if this ventilation mode is adopted.

In reality, the exhaust gas concentration may be close to the allowable concentration sometimes at random locations, which may cause visual and sensory discomfort. However, even if there is high-concentration situation for a short time, it will disappear soon due to the diffusion effect of thepiston effect of traffic.

The short duct between the air outlet and air inlet at the bottom of ventilation shaft objectively exist two states ofbypass flow and reverse flow, and sometimes the state alternating between the two due to the influence of traffic flow, natural wind, fan operation, etc. In short, there is a certain flow velocity in the short duct.

If the ratio of polluted air volume(requested air volume) to fresh air volume(design air volume), Qreq/Qr, is greater than 1.0, the air in tunnel will be polluted, which is not allowed; where the ratio is less than or equal to and close to 1.0, the air in tunnel will be clean, meeting the design requirements; where it is far less than 1.0, the air in tunnel will be clean, but it has a problem of waste and the design scheme is not economical. The 0.9 proposed in this Clause is an empirical value after a lot of design calculations.

The air supply volumeQ_b and exhaust volume Q_e are interrelated. Generally, they can't be determined independently, and their reasonable values need to be determined through trial calculation.

7.8.4 The design air volume flow of exhaust fan and air supply fan may be calculated respectively by formula(7.8.4-1) and formula(7.8.4-2):

$$p_{tote} = 1.1 \times \left(\frac{\rho}{2} \cdot v_e^2 + p_{de} - p_{se}\right) \tag{7.8.4-1}$$

$$p_{totb} = 1.1 \times \left(\frac{\rho}{2} \cdot v_b^2 + p_{db} + p_{sb}\right) \tag{7.8.4-2}$$

Where:

p_{tote}—design air pressure of exhaust fan(N/m^2);

p_{totb}—design air pressure of air supply fan(N/m^2);

p_{de}—total pressure loss in air outlet, exhaust shaft and connecting duct(N/m^2);

p_{db}—total pressure loss in air inlet, air supply shaft and connecting duct(N/m^2);

p_{se}—total pressure rise at air outlet in tunnel(N/m^2), calculated based on on-way pressure distribution;

P_{sb}—total pressure rise at air inlet in tunnel(N/m^2), calculated based on on-way pressure distribution.

Background:

The total pressure lossP_{de} or P_{db} in total pressure is the sum of pressure loss caused by bent duct, expanding duct, contracting duct, on-way resistance loss, air inlets and air outlets. The loss coefficients may refer to relevant materials(or test reports) in China's relevant professional books about fluid mechanics and aerodynamics.

7.8.5 The longitudinal ventilation with supply and exhaust shafts should be combined with jet fans to form a combined longitudinal ventilation mode through ventilation shafts and jet fans. The pressure balance of such combined longitudinal ventilation mode shall meet formula(7.8.5):

$$\Delta p_b + \Delta p_e + \Delta p_j = \Delta p_r - \Delta p_t + \Delta p_m \tag{7.8.5}$$

Background:

The exhaust system in ventilation shaft air supply and exhausting longitudinal ventilation mode or the exhaust system inlongitudinal ventilation with exhaust shafts has a very weak pressure rising effect, which is usually difficult to be in balance with the pressure required by the tunnel($\Delta p_r - \Delta p_t + \Delta p_m$). Therefore, jet fans with relatively significant pressure rising effect are always combined to solve the problem of insufficient pressure rising effect. On the whole, jet fans are auxiliary in combined ventilation (longitudinal ventilation with supply and exhaust shafts) and reasonable setting of the quantity and installation location of jet fans will have a good ventilation pressure rising effect.

7.8.6 In ventilation calculation, repeated trials shall be carried out for corresponding required air volume flow, design air volume flow and air velocity of various schemes specific to different locations of ventilation shafts and jet fans, so as to determine a reasonable on-way pressure distribution.

7.9 Longitudinal ventilation with dust collector

7.9.1 The longitudinal ventilation with dust collector shall be designed in accordance with the following provisions:

1 Longitudinal ventilation with dust collector may be applicable to extra-long highway tunnels.

2 Dust collectors shall be set at the tunnel positions before theconcentration of particulate matters reaches the design concentration.

3 Thedust removal efficiency of dust collectors may be 70% ~80%.

4 Where theconcentration of particulate matters is the main ventilation control index, the air filtered by dust collectors may be recycled; where carbon monoxide(CO) concentration is the main ventilation control index, the limit of air recycling shall be considered.

5 Various pressure losses and initial dynamic pressure of dust collectors shall be taken into full account.

6 The air velocity should be evenly distributed in the duct section near the front of dust collectors and the air velocity through the dust collector should not be greater than 9.0m/s.

7 Other smoke extraction facilities in case of fire shall be set in the tunnels adopted withlongitudinal ventilation with dust collector.

8 The dust filtered by dust collectors should be solidified and properly stored and discarded.

***Background*:**

1 For extra-long tunnels, where dust collectors are installed at appropriate positions (one or more positions) in tunnel to filter out the particulate matters inpollutants from vehicles, the ventilation shaft may be canceled or reduced, so as to increase the applicable length of longitudinal ventilation mode.

2 Generally, dust collectors are required to be installed at the tunnel positions before theconcentration of particulate matters reaches the design concentration and the air volume flow in the next zone (the tunnel zone between two dust collectors) is treated. Therefore, the setting spacing and quantity of dust collectors are affected by the value of air volume flow treated by the collector.

3 The dust removal efficiency of dust collectors is generally expressed by the dustremoval efficiency. According to the technical conditions and application of foreign equipment, the dust removal efficiency of equipment is 70% ~80%.

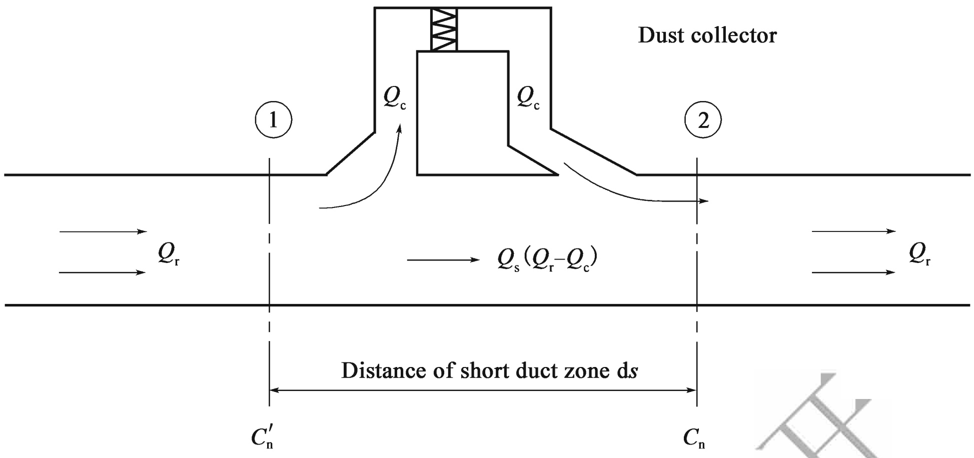
4 At present, there is no application example or research and test data of duct collector in China. By reference to relevant foreign regulations on dust collectors, the pressure loss of a dust collector itself is generally 150 ~200N/m^2.

5 The air velocity should be evenly distributed in the duct section near the front of dust collectors, so as to realize the same dust removal efficiency of each dust collection unit of the dust collector. Japan's research on the velocity of air passing through the dust collector shows that when the air velocity is 9.0m/s, the efficiency is relatively high, so the treatment speed of mainstream standard models is 9.0m/s. In light of that, this Clause is established.

6 In case of fire, the dust collector does not support the function of collecting fire smoke, so other smoke extraction facilities are needed.

7 The dust filtered by dust collectors is usually solidified for the convenience of storage or discarding. It may also be actively utilized as a mixture of other substances.

7.9.2 The longitudinal ventilation with dust collector is as shown in Figure 7.9.2. The average concentration of particulate matters relation in tunnel space before and after dust collector may be calculated by formula (7.9.2-1), and the average concentration of particulate matters at the outflow side of the dust collector in short duct zone may be calculated by formula (7.9.2-2):



Drawing 7.9.2 Longitudinal ventilation with dust collector

$$C_n = \left(1 - \frac{Q_c}{Q_r} \cdot \eta_{VI}\right) \cdot C'_n \quad (7.9.2\text{-}1)$$

$$C_D = C'_n + \frac{Q_{req(s)}}{Q_s} \quad (7.9.2\text{-}2)$$

Where:

C_n—average concentration of particulate matters ratio in tunnel space after dust collection;

Q_e—air volume flow filtered by dust collector(m^3/s);

C'_n—average concentration of particulate matters ratio in tunnel space before dust collection;

C_D—average concentration of particulate matters ratio at the outflow side of short duct zone;

η_{VI}—dust removal efficiency(%);

$Q_{req(s)}$—required air volume flow in short duct zone(m^3/s);

Q_s—design air volume flow in short duct zone(m^3/s), $Q_s = Q_r - Q_c$.

Background:

Dust collectors have been successfully applied in highway tunnels in Japan and Norway.

The ventilation air velocity in tunnel is generated under thepiston effect of traffics or mechanical effect of other ventilation facilities. Therefore, it may not rely on the pressure rise generated by the air volume flow Q_c blown by the dust collector.

Generally, there are two installation modes of dust collectors: one is the distributed installation mode in which small-capacity dust collectors are arranged in a distributed manner along the axis of tunnel arch; another is to install large-capacity dust collectors in the side tunnels of the main tube section. Where large-capacity dust collectors are adopted, the air inlet size is restricted by the structure, which is generally the same as the air inlet inlongitudinal ventilation with supply and exhaust shafts. The airflow is blown out at a relatively high speed. Therefore, the pressure rise may be calculated according to the pressure mode of longitudinal ventilation with supply and exhaust shafts and the relation $Q_c = Q_b = Q_e$ may be considered.

7.10 Full transverse and semi-transverse ventilation modes

7.10.1 The full transverse and semi-transverse ventilation modes may be applicable to both uni-directional and bi-directional tunnels.

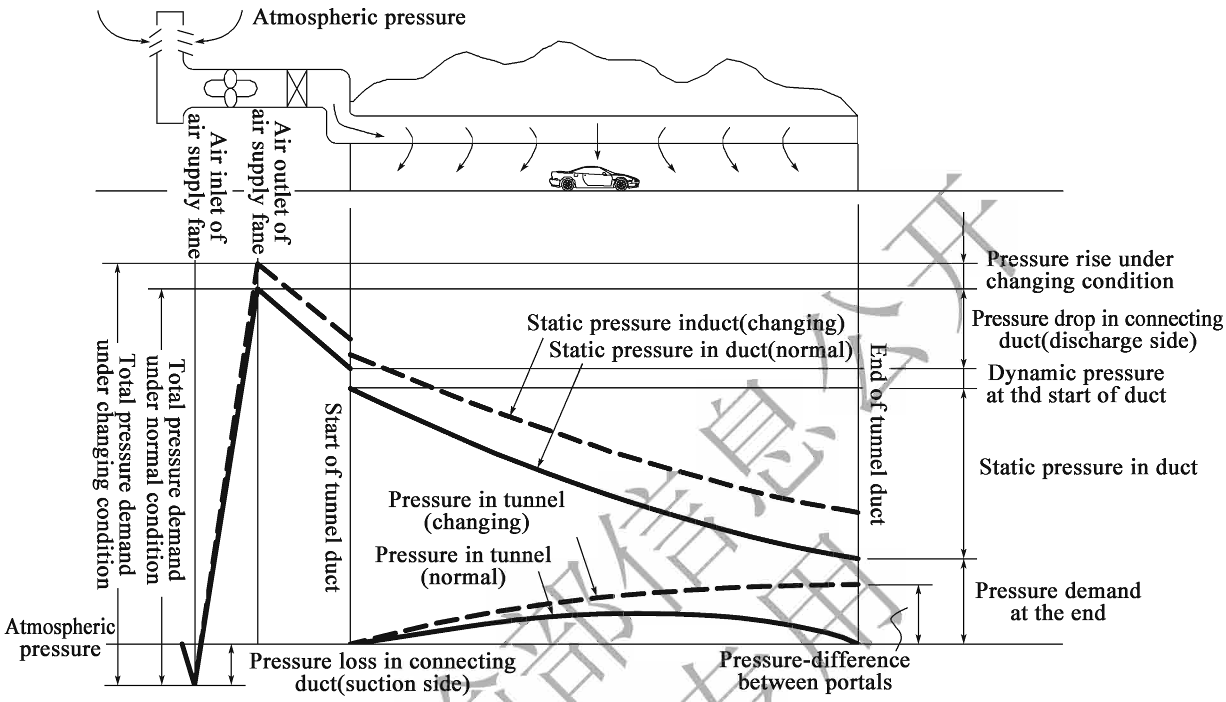
Background:

Compared with longitudinal ventilation modes, the airflow offull transverse ventilation mode forms a circulation on the tunnel cross section for air exchange, with relatively low air velocity in lanes and good smoke exhaust effect. Therefore, the full transverse ventilation mode is especially suitable for extra-long bi-directional tunnels. The results of semi-transverse ventilation modes applied at home and abroad show that the exhausting semi-transverse ventilation mode shows a poor ventilation effect and high energy consumption when applied to uni-directional tunnels. Therefore, this Clause is established.

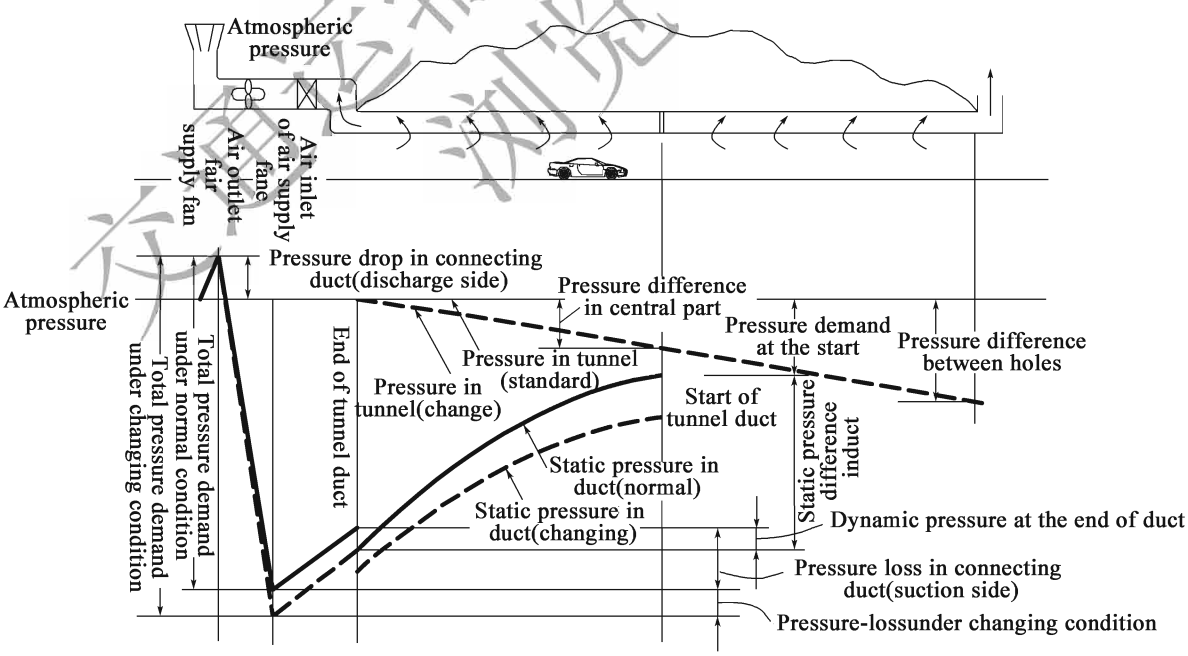
7.10.2 The pressure modes of full transverse and semi-transverse ventilation modes may be as shown in Figure 7.10.2.

Background:

The pressure modes offull transverse ventilation modes are generally as shown in Figure 7.10.2. Where there is no pressure difference(Δp_m) between two tunnel portals caused by natural wind and meteorological temperature difference, it is indicated by (pressure) solid lines in the Figure and is considered as the normal ventilation state; where there is pressure difference between two tunnel portals, the air pressure in tunnel shall be changed and the pressures at the start and end of duct shall rise or drop accordingly, indicated by (pressure) dashed lines in the Figure. The fan total pressure is generally determined based on the design total pressure indicated by dashed lines.



a)Pressure distribution in supply duct system (one-duct)



b)Pressure distribution in exhaust duct system (double-duct)

Figure 7.10.2 Pressure mode offull transverse and semi-transverse ventilation

7.10.3 The air pressures in air-supply and exhaust ducts of full transverse and semi-transverse ventilation modes may be calculated in accordance with the following requirements:

1 Where thesupply duct section A_b remains unchanged along the tunnel axis and the same quantity of fresh air is blown into the tunnel through the supply duct, the dynamic pressure at the start of supply duct may be calculated by formula (7.10.3-1) and the static pressure difference in supply duct may be calculated by formula (7.10.3-2):

$$p_b = \frac{\rho}{2} \cdot v_{bi}^2 \tag{7.10.3-1}$$

$$p_{bi} - p_{b0} = k_b \cdot \frac{\rho}{2} \cdot v_{bi}^2 \tag{7.10.3-2}$$

Where:

P_b—dynamic pressure at the start of supply duct (N/m^2);

v_{bi}—air velocity at the start of supply duct (m/s), $v_{bi} = \frac{Q_b}{A_b}$;

P_{bi}—static pressure at the start of supply duct (N/m^2);

P_{b0}—static pressure at the end of supply duct (N/m^2);

K_b—loss coefficient of air pressure in supply duct, $k_b = \frac{\lambda_b}{3} \cdot \frac{L_b}{D_b} - 1$;

D_b—hydraulic diameter of supply duct (m);

L_b—length of supply duct (m).

2 Where the exhaust duct sectionA_e remains unchanged along the tunnel axis and the same quantity of polluted air is exhausted into the exhaust duct, the dynamic pressure at the end of exhaust duct may be calculated by formula (7.10.3-3) and the static pressure difference in exhaust duct may be calculated by formula (7.10.3-4):

$$p_e = \frac{\rho}{2} \cdot v_{e0}^2 \tag{7.10.3-3}$$

$$p_{ei} - p_{e0} = k_e \cdot \frac{\rho}{2} \cdot v_{e0}^2 \tag{7.10.3-4}$$

Where:

p_e—dynamic pressure at the end of exhaust duct (N/m^2);

v_{e0}—air velocity at the end of exhaust duct (m/s), $v_{e0} = \frac{Q_e}{A_e}$;

p_{ei}—static pressure at the start of exhaust duct (N/m^2);

p_{e0}—static pressure at the end of exhaust duct (N/m^2);

K_e—loss coefficient of air pressure in exhaust duct, $k_e = \frac{\lambda e}{3} \cdot \frac{Le}{De} + 2$;

D_e—hydraulic diameter of exhaust duct(m);

L_e—length of exhaust duct(m).

3 The pressure demand at the end ofsupply duct shall guarantee the uniform distribution of semi-transverse supply ventilation system, which may be 150N/m^2.

4 The pressure demand at the start of exhaust duct shall guarantee the uniform exhaust, which may be 100N/m^2.

***Background*:**

1 In order to determine the origin value of static pressure at the end ofsupply duct, the pressure demand at the end of supply duct needs to be determined($P_{b0} - P_{r0}$). Even if the pressure distribution in the tunnel changes due to the changes of meteorological conditions or traffic conditions, the uniformity of air volume flow distribution can still be guaranteed. The value includes the pressure difference Δp_m caused by natural wind between two portals.

2 In order to determine the origin value of static pressure of exhaust duct, the pressure demand at the start of exhaust duct needs to be determined($P_{ri} - P_{ei}$). Sufficient start pressure needs to be designed to overcome the negative pressure after passing of vehicles or adverse impact caused by change of meteorological conditions, so as to ensure the uniformity of exhaust. The value includes the pressure difference Δp_m caused by natural wind between two portals.

3 ~ 4 The required pressures at the end of the supply duct and at the start of the exhaust duct are determined by reference to the test results from Japan's Tokyo-Nagoya Highway Tunnel.

According to some engineering practices abroad, the relation between tunnel air pressure andsupply duct air pressure may be as indicated in Figure 7-6, which of course is related to the shape and size of supply duct. However, in actual tunnels, there are few cases in which($P_{b0} - P_{r0}$)$_{min}$ is less than the pressure demand of exhaust duct. All the above mentioned pressures at the end of supply duct and pressures at the start of exhaust duct are measurement engineering results and natural factors have been considered. Therefore, the meteorological pressure difference Δp_m between two portals has been included in the measured pressure values.

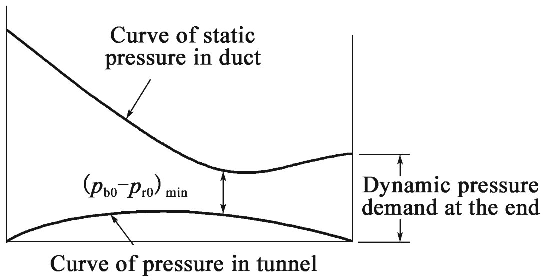


Figure 7-6 Relation between pressure demand at the end ofsupply duct and minimum exhaust air pressure

7.10.4 The air pressure in tunnel may be determined according to the following principles:

1 Where thefull transverse ventilation mode is adopted, the value of static pressure in tunnel under normal atmospheric pressure may be 0.

2 Wheresemi-transverse supply ventilation mode is adopted, the design air velocity at point x in tunnel may be calculated by formula(7.10.4-1):

$$v_r(x) = \frac{q_b}{A_r} \cdot x \tag{7.10.4-1}$$

Where:

$v_r(x)$—air velocity at point x in tunnel(m/s);

q_b—air-supply volume per unit length [$m^3/(s \cdot m)$];

x—Xdistance from the zero point($v_r = 0$)(m).

1) In the zone from the entrance to the zero point ofuni-directional tunnel, the distribution of air pressure in tunnel may be calculated by formula(7.10.4-2):

$$p_{rc} - p_r(x_1) = \left(\frac{\lambda}{3} \cdot \frac{x_1}{D_r} + 2\right) \cdot \frac{\rho}{2} \cdot v_r^2(x_1) + \alpha \cdot \frac{x_1}{L} \cdot \frac{\rho}{2} \cdot \left[v_t^2 + v_t \cdot v_r(x_1) + \frac{1}{3} \cdot v_r^2(x_1)\right] \tag{7.10.4-2}$$

Where:

x_1—distance from the zero point to the tunnel entrance(m);

$p_r(x_1)$—tunnel static pressure at point x_1 (N/m^2);

p_{rc}—static pressure at the zero point(N/m^2);

$v_r(x_1)$—tunnel air velocity at point x_1 (m/s);

α—coefficient ofpiston effect of traffic, $\alpha = \frac{A_m}{A_r} \cdot \frac{N \cdot L}{3600 \times v_t}$;

2) In the zone from the zero point to the exit ofuni-directional tunnel, the distribution

of air pressure in tunnel may be calculated by formula(7.10.4-3):

$$p_{\mathrm{rc}} - p_{\mathrm{r}}(x_2) = \left(\frac{\lambda}{3} \cdot \frac{x_2}{D_{\mathrm{r}}} + 2\right) \cdot \frac{\rho}{2} \cdot v_{\mathrm{r}}^2(x_2) - \alpha \cdot \frac{x_2}{L} \cdot \frac{\rho}{2} \cdot \left[v_{\mathrm{t}}^2 - v_{\mathrm{t}} \cdot v_{\mathrm{r}}(x_2) + \frac{1}{3} \cdot v_{\mathrm{r}}^2(x_2)\right] \tag{7.10.4-3}$$

Where:

x_2—distance from the zero point to the tunnel exit(m);

$p_{\mathrm{r}}(x_2)$—tunnel static pressure at point x_2 (N/m^2);

$v_{\mathrm{r}}(x_2)$—tunnel air velocity at point x_2 (m/s);

3) In case of bi-directional traffic and equal traffic volume in two directions, the distribution of air pressure in tunnel may be calculated by formula(7.10.4-4):

$$p_{\mathrm{rc}} - p_{\mathrm{r}}(x) = \left(\frac{\lambda}{3} \cdot \frac{x}{D_{\mathrm{r}}} + 2\right) \cdot \frac{\rho}{2} \cdot v_{\mathrm{r}}^2(x) + \alpha \cdot \frac{x}{L} \cdot \frac{\rho}{2} \cdot v_{\mathrm{t}} \cdot v_{\mathrm{r}}(x) \tag{7.10.4-4}$$

***Background*:**

The distribution of air pressure in tunnel under semi-transverse ventilation mode as shown by the formula in this Clause is calculated on the premise that the air supply volumeq_{b} is uniformly distributed along the unit length (usually under air supply condition at both portals). Where the air supply at single portal is considered, the tunnel air pressure at the end of supply duct is usually zero and the tunnel air pressure at this position is usually taken as zero in the calculation of total pressure of air supply fan. Where more than two supply ducts are adopted that the tunnel is divided into more than two ventilation zones, the graphical method as shown in Figure 7-7 may be adopted, namely to obtain the tunnel air pressure by the relative position relation between the tunnel air pressure distribution and duct zone.

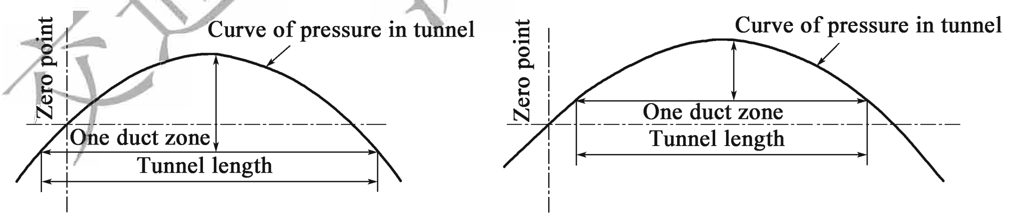


Figure 7-7 Sketch of tunnel air pressure(under air supply condition at both portals)

7.10.5 The pressure loss in connecting duct may be calculated by formula(7.10.5):

$$\Delta p_{\mathrm{d}} = \sum_{i=1}^{m} \zeta_i \cdot \frac{\rho}{2} \cdot v_i^2 + \sum_{i=1}^{n} \lambda_i \cdot \frac{L_i}{D_i} \cdot \frac{\rho}{2} \cdot v_i^2 \tag{7.10.5}$$

Where:

Δp_{d}—pressure loss in connecting duct(N/m^2);

ζ_i—the i^{th} local loss coefficient;

λ_i—on-way resistance loss coefficient in Zone i;

v_i—air velocity in Zone i(m/s);

L_i—length of Zone i(m);

D_i—hydraulic diameter of Zone i(m);

m—local change quantity of connecting ducts;

n—number of zones of connecting duct.

7.10.6 The design total pressure of fan may be determined according to the following principles:

1 The design total pressure P_{btot} of air supply fan in semi-transverse supply ventilation or full transverse ventilation mode may be calculated by formula(7.10.6-1):

P_{btot} = 1.1 × (air pressure of tunnel + pressure demand at the end of supply duct + static pressure difference of supply duct + dynamic pressure at the start of supply duct + pressure loss of connecting duct) (7.10.6-1)

2 The design total pressure P_{etot} of exhaust fan in full transverse ventilation mode may be calculated by formula(7.10.6-2):

P_{etot} = 1.1 × (pressure demand at the start of exhaust duct + static pressure difference of exhaust duct-dynamic pressure at the end of exhaust duct + pressure loss in connecting duct) (7.10.6-2)

3 The pressure loss of the fan itself shall also be considered for the final determination of design total pressure of the fan.

Background:

The design total pressure of air supply fan includes the sum of various pressure loss during the process that the air is sucked in through the ventilation tower inlet and blown into the tunnel through connecting duct, supply duct and air inlet and then exhausted through air outlet, and also includes the tunnel air pressure. The tunnel air pressure in this Clause refers to the sum of the in-tunnel piston effect of traffic, resistance of natural wind and ventilation resistance.

The design total pressure of exhaust fan shall include the sum of various pressure loss during the process that the air is sucked in the air outlet and then exhausted through the ventilation tower outlet after passing through exhaust duct and connecting duct. The tunnel static pressure infull transverse ventilation mode under normal atmospheric pressure is usually zero, so this pressure is not considered in formula(7.10.6-2).

Common units and unit conversion influid mechanics are as shown in Appendix D. The examples of ventilation calculation are as shown in Appendix E.

8 Duct

8.1 General

8.1.1 The duct design shall give comprehensive consideration to the construction and operation costs of ventilation system.

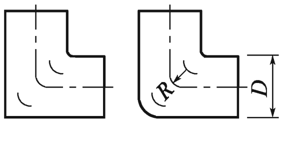
***Background*:**
The duct mainly consists ofmain duct, connecting duct and the internal duct of fan room. The connecting duct connects the main tube, main duct, ventilation shaft and fan room.

8.1.2 The section change and number of bent ducts shall be reduced in duct design.

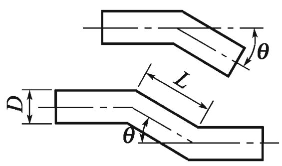
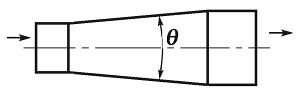
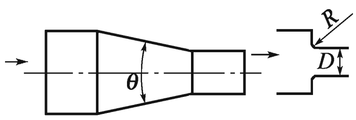
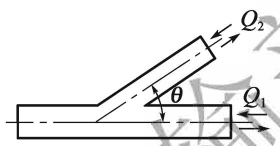
***Background*:**
The total pressure shall remain unchanged along the way if there's no resistance inthe duct. Since the total pressure will change due to the pressure loss caused by section change or bent ducts, therefore the section change or number of bent ducts shall be reduced as far as possible. With regard to some special variable cross sections or bent ducts, the local pressure loss is determined by means of numerical or physical simulation test for research and analysis.

The deformation of duct usually includes the forms specified in Table 8-1.

Table 8-1 Forms of duct deformation

Deformation	Diagram	Explanation
Bending		When$R < 1.6D$, corner blade is installed to reduce loss and flow deflection. The inner side of bending is rounded. The outer side of bending may be not rounded.

continued

Deformation	Diagram	Explanation
Zigzag		The zigzag with a $\theta > 30°$ is avoided to the greatest extent. AppropriateL/D and θ is selected to reduce the loss in case of continuous zigzag. For example, when $\theta = 30°$, $L = 3D$ is the best.
Expanding		The loss is the minimum when $\theta = 6° \sim 10°$. The loss is the maximum when $\theta = 60° \sim 70°$; so it' s best to expand the θ to 180°.
Contracting		Sudden reduction shall be prevented. It' s better thatθ < 60°; when θ > 60°, it should be made trumpet shaped to reduce loss. The radius of trumpet should be greater than 0.1D and the ideal value is about 0.3D.
Diverging and merging		The loss of diverging and merging is affected by air quantity ratioQ_1/Q_2 and area ration and cannot be treated as the same; but the θ shall be as small as possible.

8.1.3 The bending, zigzag, expanding and contracting, diverging and merging of duct should have smooth transition and the internal face shall be smooth.

8.1.4 Guide blade may be placed at the bottom of ventilation shaft and the bent duct; the air deflector may be placed at duct variable section, merging location, air inlet and air outlet; the duct in front and at back of fan shall be free from flow deflection, reverse flow and vortex flow.

Background:

In order to reduce airflow resistance, the guide blade may be placed at the bottom of ventilation shaft and thebent duct; and air deflector may be placed at duct variable section, confluence, air inlet and air outlet.

8.1.5 The design of connecting duct in fan room shall give consideration to the air volume flow control and the operating mode of fan in case of emergency to determine a reasonable shape of duct and switching mode.

8.1.6 The water spray systems which are used to cool down the tunnel high-temperature fire smoke may be installed in the exhaust duct.

Background:

Since the tunnel is a relatively enclosed space, the temperature will go up to over 1,200℃ quickly in the event of a fire, which will easily cause concrete spalling, exposed structural reinforcing bar and damage of tunnel structure. When the exhaust duct is also served as the smoke duct, thewater spray systems may be used to cool down the high-temperature flue gas, in order to protect the duct structure.

8.1.7 The duct partition shall be with a good air tightness, corrosion resistance and fire resistance; and its structure shall meet relevant requirements of strength and durability.

8.1.8 Protective netting shall be installed at the duct vent to prevent foreign matters from entering.

8.1.9 Water-proofing and drainage measures shall be taken in duct to avoid water leakage and standing water, and prevent the duct vent from icing up.

8.1.10 The pressure loss coefficient of each type of duct may be taken according to Appendix C. When deformation occurs in duct continuously within a short distance, the margin of pressure loss shall be considered. If necessary, the specific pressure loss may be determined by simulation test.

Background:

Theresistance loss coefficient of duct wall and the deformation loss coefficient of duct are closely related to the magnitude of pressure loss. When deformation (bending, zigzag, sudden expansion and reduction) occurs in the duct continuously within a short distance, and the pressure loss is very large, the specific pressure loss coefficient may be determined by test.

8.2 Main duct

8.2.1 The main duct should be arranged longitudinally along tunnel and be placed on the top of tunnel.

Background:

Themain duct of tunnel is generally installed in the transverse or semi-transverse ventilation system, and placed on the top of tunnel longitudinally along tunnel, and also may be placed under or on the side of tunnel, as shown in Figure 8-1.

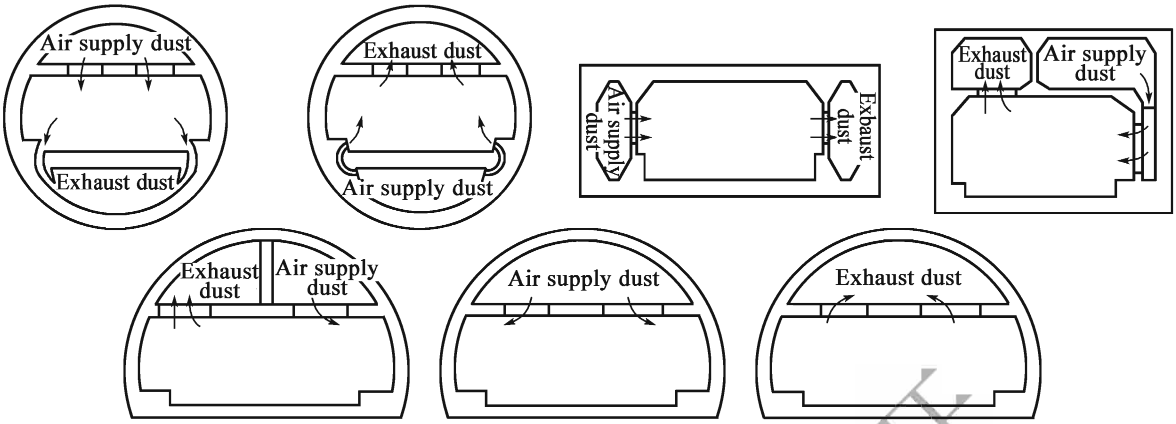


Figure 8-1　Diagram of tunnel' smain duct arrangement

8.2.2　The number of sections of main duct and the section size shall give comprehensive consideration to such factors as the division of tunnel' s ventilation zones, initial construction cost, ventilation system operation and maintenance costs and be determined through technical and economic comparison.

***Background*:**

As for transverse ventilation mode, a ventilation zone refers to a zone that can independently control the air volumeflow and is completely separated from other ventilation zones; the duct of a long tunnel is usually divided into 2 or more zones to control the tunnel ventilation sectionally.

When ventilation mode and required air volume flow are determined, the air supply volume or exhaust volume ofmain duct may be calculated. Then, if the length of one ventilation zone is increased, the main duct sectional area will increase accordingly, thus the construction cost will also increase. Therefore, economical design of duct shall be carried out by combining the relationship between the number of sections of main duct and the main duct sectional area with tunnel layout and terrain condition.

8.2.3　The design air velocity of main duct should be in the range of 13.0 ~ 20.0m/s.

***Background*:**

When the ventilation zones and their design air volume flow are determined, the design air velocity ofmain duct will directly affect the section size of main duct and tunnel, thus the initial project investment will be greatly affected accordingly. The air velocity value of main duct is inversely proportional to the tunnel' s section size. Smaller tunnel section is conducive to saving project investment, but larger air velocity of main duct will increase the installed motor power of ventilation system, resulting in an increase in the long-term operation cost of ventilation system.

Therefore, according to domestic and overseas technical data, application of engineering and research result, the design air velocity ofmain duct is economical and reasonable in the range of 13.0 ~ 20.0m/s.

8.2.4 The roof bulkhead design for main duct installed on the top of tunnel shall be designed in accordance with the following provisions.

1 The design load shall consist of dead loads such as the dead load ofroof bulkhead and its ancillary components and variable loads such as wind loads and pedestrian loads. The wind loads may refer to the maximum air supply (exhaust) pressure of ventilation design. The pedestrian loads may be 1,000N/m^2.

2 The maximum deflection under the joint action of the dead load and the larger between windload and pedestrian load shall not be greater than 1/400 of the roof bulkhead span.

3 The standard thickness ofroof bulkhead should not exceed 20cm. In particular cases, the thickness of roof bulkhead may be increased appropriately.

***Background*:**

1 Thepedestrian loads of roof bulkhead of several Japanese highway tunnels is 1,000N/m^2, which is based on mature experience. Therefore, the value of this Clause refers to that value.

2 The allowable deflection ofroof bulkhead shall be 1/400 of that specified in the *Specifications for Design of Highway Tunnels* (JTG D70—2004).

3 This Clause proposes that the standard thickness ofroof bulkhead should be not greater than 20cm, but it must be determined after calculation according to the actual load and material characteristics as well as the specific function of use. When the tunnel lighting is embedded in the roof bulkhead or under other special circumstances, the thickness of roof bulkhead may be appropriately increased.

8.2.5 When the main duct is served as the smoke duct, the influence of high-temperature fire on the structure of duct shall be considered. The fire endurance of main duct partition shall not be less than 1.0h.

***Background*:**

For transverse ventilation and centralized smoke duct, theroof bulkhead will directly withstand high temperature in case of fire, and the structure is prone to deformation and peeling, resulting in more serious consequences such as air leakage and even collapse. Once the duct and roof bulkhead are damaged, it is very hard to repair or replace, thus this Clause is made.

8.3 Connecting duct

8.3.1 The design air velocity of connecting duct should be not greater than 13.0m/s.

8.3.2 The connection between connecting ducts, connecting duct and structures at both ends shall be noticed in design.

***Background*:**
The design of sectional area, length, section shape and connecting type of connecting duct shall reduce the air pressure loss of duct and be economical.

8.4 Air supply opening and air exhaust opening

8.4.1 The air supply opening design of main duct shall be in accordance with the following provisions:

1 The air supply opening should be placed below the tunnel side wall, and its height should be approximately equal to the height of vehicle exhaust pipe from pavement. Thesupply duct shall be connected with the air supply opening with air drift.

2 The area of air supply opening should be calculated by the maximum required air volume flow and the air velocity of 6.0 ~ 8.0m/s when outlet is fully opened.

3 For the tunnel withfull transverse ventilation, the distance between air supply openings should be 5 ~ 6m; and for the tunnel with semi-transverse ventilation, the distance between air supply openings should be 25m.

8.4.2 The air exhaust opening design of main duct shall be in accordance with the following provisions:

1 The location of air exhaust opening shall be determined according to the section form of tunnel structure and the layout plan ofmain duct. The air exhaust opening should be directly connected with the exhaust duct.

2 The area of air exhaust opening should be calculated by the maximum required air volume

flow and the air velocity of not more than 4.0m/s when inlet is fully opened.

3 The air exhaust opening shall be staggered between two air supply openings, and the distance between air exhaust openings should be twice the distance between air supply openings.

Background:

8.4.1 ~ 8.4.2 The locations of air supply opening and air exhaust opening are determined according to the section form of tunnel structure and the layout plan ofmain duct. When the tunnel section is in the form of a mountain tunnel(horseshoe section) and the full transverse ventilation is adopted, the layout of air supply and air exhaust openings is usually seen in Figure 8-2.

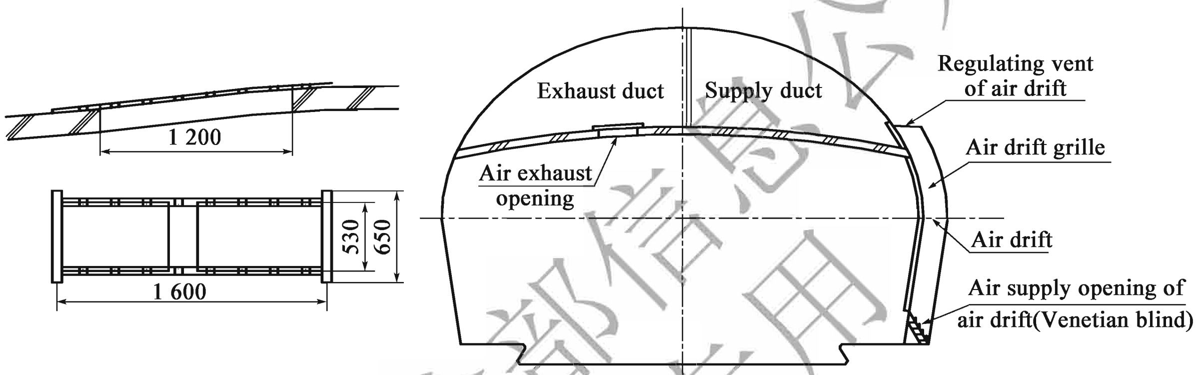


Figure 8-2 Example of locations of the air supply opening and air exhaust opening(unit: mm)

The Clauses propose that the installation height of air supply opening should be approximately the same as the height of vehicle exhaust pipe from pavement, in order to dilute the vehicle exhaust as soon as possible, and form air exchange with the air exhaust opening. If the fresh air directly enters into tunnel through thesupply duct, and form air exchange in the upper part of tunnel; while the polluted air in the lower part of tunnel fails to be exchanged, thus the ventilation effect will be poor. On the other hand, the air supply speed will increase due to the short distance between the air supply opening and the axial fan and decrease due to their long distance, which will result in non-uniform air velocity. In order to solve this problem, as shown in Figure 8-2, the air drift and regulating vent shall be installed between supply duct and air supply opening, and the air velocity in the tunnel may be basically uniform.

The staggered arrangement of air exhaust opening and air supply opening may avoid airflow shortcut, and form effective air dilution, flow and exchange in the tunnel section to ensure ventilation effect.

8.4.3 The opening adjustment of air supply and air exhaust openings shall meet the following requirements:

1 The opening adjustment shall meet the air volumeflow distribution requirements in the state of tunnel design.

2 The opening setting should be carried out in a set of 10 openings.

8.4.4 The opening size adjustment of supply and air exhaust openings may be carried out in the following order:

1 Test theresistance loss coefficient λ_b in duct.

2 Adjust the openingsize for the first time.

3 Test the static pressure distribution and air velocity distribution in duct.

4 Adjust the opening size again.

5 Set the opening size.

Background:
8.4.3 ~ 8.4.4 In order to uniformly convey fresh air into tunnel and discharge polluted air in time, it is necessary to adjust the opening, and put forward working requirements for opening adjustment.

There are generally 3 methods to test the ventilation condition: the method to calculate flow according to the flow rate and the opening sectional area, the method of estimation according to the static pressure distribution in duct, and the method of estimation according to the air velocity distribution in duct.

8.5 Air inlet and air outlet

8.5.1 The design shall be in accordance with the following provisions:

1 The air inlet should be installed at the tunnel arch, and the design air velocity of air inlet should be 25.0 ~ 30.0m/s, and the air supply direction shall be consistent with the axial direction of tunnel.

2 The sectional area of air inlet shall be determined according to the air supply volume into tunnel and the design air velocity of air inlet.

Background:

Air inlet refers to the inlet that is connected to the main tube and conveys fresh air into the main tube when it is longitudinally ventilated. In order to obtain a large pressure rise, the jet speed of air inlet is 25.0 ~30.0m/s generally. Higher air velocity is bad for traffic safety. Therefore, the inlet should be placed at the tunnel arch and required to be consistent with the axial direction of tunnel.

The faster the air velocity of air inlet, the better the ventilation pressure rising effect, but excessive air velocity may cause an adverse impact on vehicles, so generally the air velocity shall be not greater than 30.0m/s. For bi-directional traffic, the traffic pressure rise cannot be utilized, and usually the upper limit of 30.0m/s; foruni-directional traffic, the traffic pressure rise is remarkable and usually the lower limit of 25.0m/s.

8.5.2 The air outlet design shall be in accordance with the following provisions:

1 The air outlet should be placed on the tunnel side wall, and its bottom surface shall be at the same height as the tunnel maintenance path; the design air velocity of air outlet should not exceed 8.0m/s.

2 The sectional area of air outlet should not be larger than that of the main tube.

3 The air outlet shall have a protective netting and accept anti-corrosive treatment.

4 In bi-directional tunnel, the angle between air outlet and main tube should be 90°; while in theuni-directional tunnel, the angle between air outlet and main tube may be 30° ~90°.

Background:

Air outlet refers to the outlet that is connected to main tube and discharges polluted air from main tube when it is longitudinally ventilated. From the perspective of traffic safety, the design air velocity of air outlet should not be greater than the design air velocity in tunnel. Therefore, the design air velocity of air outlet should not exceed 8.0m/s.

A protective netting is required for the air outlet to prevent foreign matters from intaking and damaging fan blades, and also to protect the safety of maintenance personnel. Due to motor vehicle exhaust pollution and the humid environment in tunnel, the protective netting of air outlet may be corroded. Therefore, the protective netting needs to be anti-corrosive or made of stainless steel.

In consideration of the implementation of tunnel structure and the saving of project cost, this Clause proposes that the bottom surface of air outlet shall be substantially at the same height with the tunnel maintenance path, and the exhaust direction is perpendicular to the axial direction of tunnel. In practice, the air outlet may intersect with tunnel axially.

8.6 Ventilation valves

8.6.1 When 2 or more air supply fans are installed in parallel in tunnel, ventilation valves shall be installed at the front or rear end of each air supply fan.

8.6.2 The ventilation valves of ventilation fan in connecting duct shall be in accordance with the following provisions:

1 Theventilation valves should be a parallel multi-blade regulating valves.

2 Theventilation valves shall be coordinated with air supply fan, and its structure shall be with a good air tightness; if the pressure difference is not greater than 2000Pa, the air leakage per unit area of air valve shall not exceed $0.1m^3/(s \cdot m^2)$.

3 The opening and closing time ofventilation valves shall not exceed 30s.

Background:
The air regulating valves shall be with a good air tightness, and its relative air leakage may be controlled within about 5%; and thus theventilation valves should be adjustable due to good regulation performance. The air regulating valve blades are classified into the gate type and butterfly type, and the ventilation valves are classified into parallel multi-blade regulating valve, split-type multi-blade regulating valve, diamond multi-blade regulating valve and gate valve, and may be opened and closed with the running and shutdown of air supply fan.

8.6.3 The ventilation valves of air supply (exhaust) opening of main duct shall be in accordance with the following provisions:

1 When themain duct is also served as a smoke duct, the adjustable smoke exhaust valve shall be installed for air supply (exhaust) opening.

2 Theventilation valves shall be with a good air tightness.

3 Theventilation valves shall be automatically opened and closed in groups, and comply with relevant requirements of the current *Specifications for Fire Protection Design of Buildings* (GB 50016).

9 Fan Room and Ventilation Shaft

9.1 General

9.1.1 The design of fan room and ventilation shaft shall give comprehensive consideration to factors such as functional requirements, site selection, construction condition, environmental protection, maintenance and repair, operation management and landscape coordination.

9.1.2 The fan room shall provide space for axial fan, electrical equipment, control device and other auxiliary equipment, reserve space for equipment maintenance and be set up with the passage for large equipment handling and service corridor.

9.1.3 The connection between fan room and duct shall be sealed.

9.1.4 Water-proofing and drainage measures shall be taken for fan room and ventilation shaft.

9.1.5 Apart from provisions of the *Guidelines*, the requirements of relevant specifications for buildings design shall also be abided by. Apart from provisions of the *Guidelines*, the design of ventilation shaft shall also meet the requirements of tunnel structure design in the current *Specifications for Design of Highway Tunnels* (JTG D70) shall also be abided by.

***Background*:**

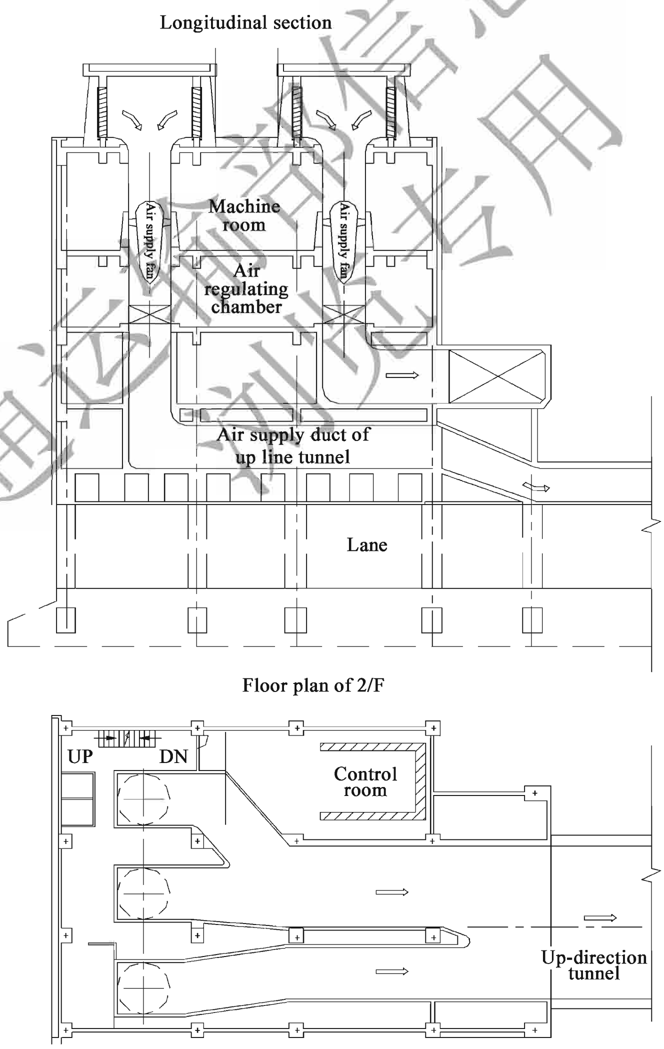
9.1.1 ~ 9.1.5 The arrangement of fan room shall meet the requirements of installation, overhaul and maintenance of ventilation system and related facilities. The sites of fan room and ventilation shaft are limited by factors such as terrain, geology, construction and management convenience, and the rationality of their location affects the project cost and operation management cost. Therefore, fan room shall meet the functional requirements, and be appropriately located with reliable structure, harmonious appearance for the convenience of maintenance and operation management.

9.2 Aboveground fan room

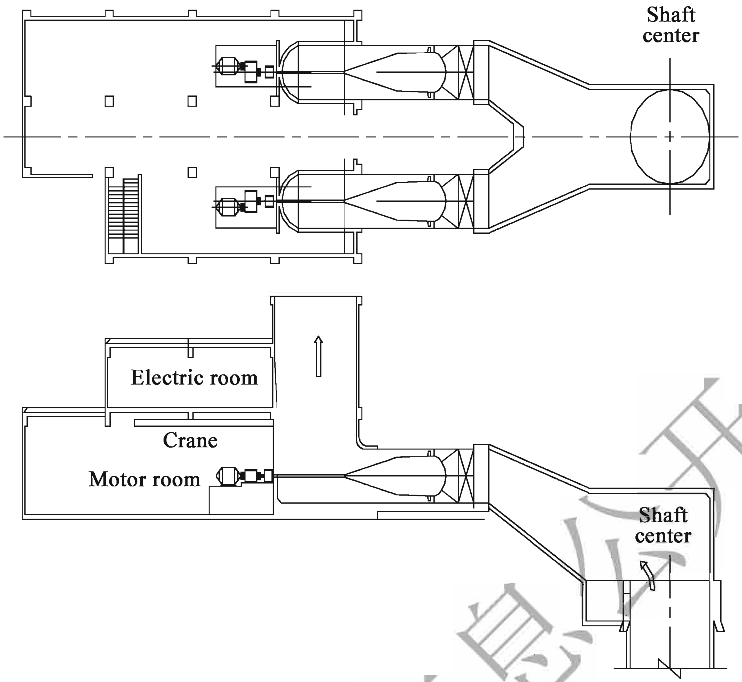
9.2.1 The design of aboveground fan room shall be determined in line with the surrounding terrain condition of tunnel portal or ventilation shaft, the transportation of large facilities and equipment, the work convenience of management personnel and the axial spacing between two tunnel portals, and shall coordinate with environment.

Background:

When longitudinal ventilation with Saccardo nozzle or transverse ventilation is adopted, fan room is usually seated at the tunnel portal, and its location and form shall be determined according to the terrain condition at tunnel portal. It is generally seated between two tunnel portals or at one side of cutting. The arrangement between two tunnel portals is shown in Figure 9-1. When zoned ventilation is adopted, fan room is located at the surface of ventilation shaft opening, as shown in Figure 9-2.



igure 9-1 Case of fan room between two tunnel portals



re 9-2　Case of fan room at the ventilation shaftopening (surface)

When fan room is placed between two tunnel portals, in order to protect traffic from oppression, it is necessary to pay attention to the harmony with the environment at tunnel portal.

Longitudinal section

9.2.2　The arrangement of aboveground fan room shall avoid affecting the life of residents and environmental landscape nearby.

***Background*:**

The arrangement of aboveground fan room may damage the natural environment and affect the life of residents nearby. Such affect needs to be considered in design. For example, the arrangement of aboveground fan room near town may bring noise to resident nearby and affect air quality, and may affect the environmental landscape.

9.3　Underground fan room

9.3.1　The design of underground fan room shall be determined by giving comprehensive consideration to the factors such as geological condition, safety and economy. It should be located in a place with favorable condition of surrounding rock mass.

***Background*:**

When multi zone ventilation systems with shafts are adopted for tunnels and it is difficult to build aboveground fan rooms, underground fan rooms can be employed, as shown in Figure 9-3. According to some overseas technical data, before the 1990s, tunnel fan rooms were usually located near tunnel portals or on surface close to ventilation shaftopenings. But after the 1990s, some countries, especially Japan, often built fan rooms underground, i. e. , in the mountain whether the bottom of ventilation shaft connects with the main tunnel when a multi zone ventilation system with shafts is adopted, which is convenient for technical personnel to maintain and manage equipment. Generally, such a method raises project costs in comparison to placement of fans rooms outside tunnels, but it saves land and protects vegetation environment. Since 2003, China has also begun to employ underground fan rooms. Typical projects include the Qinling Zhongnan Mountain Tunnel of G65 Baotou-Maoming Expressway and the Fangdou Mountain Tunnel of G50 Shanghai-Chongqing Expressway.

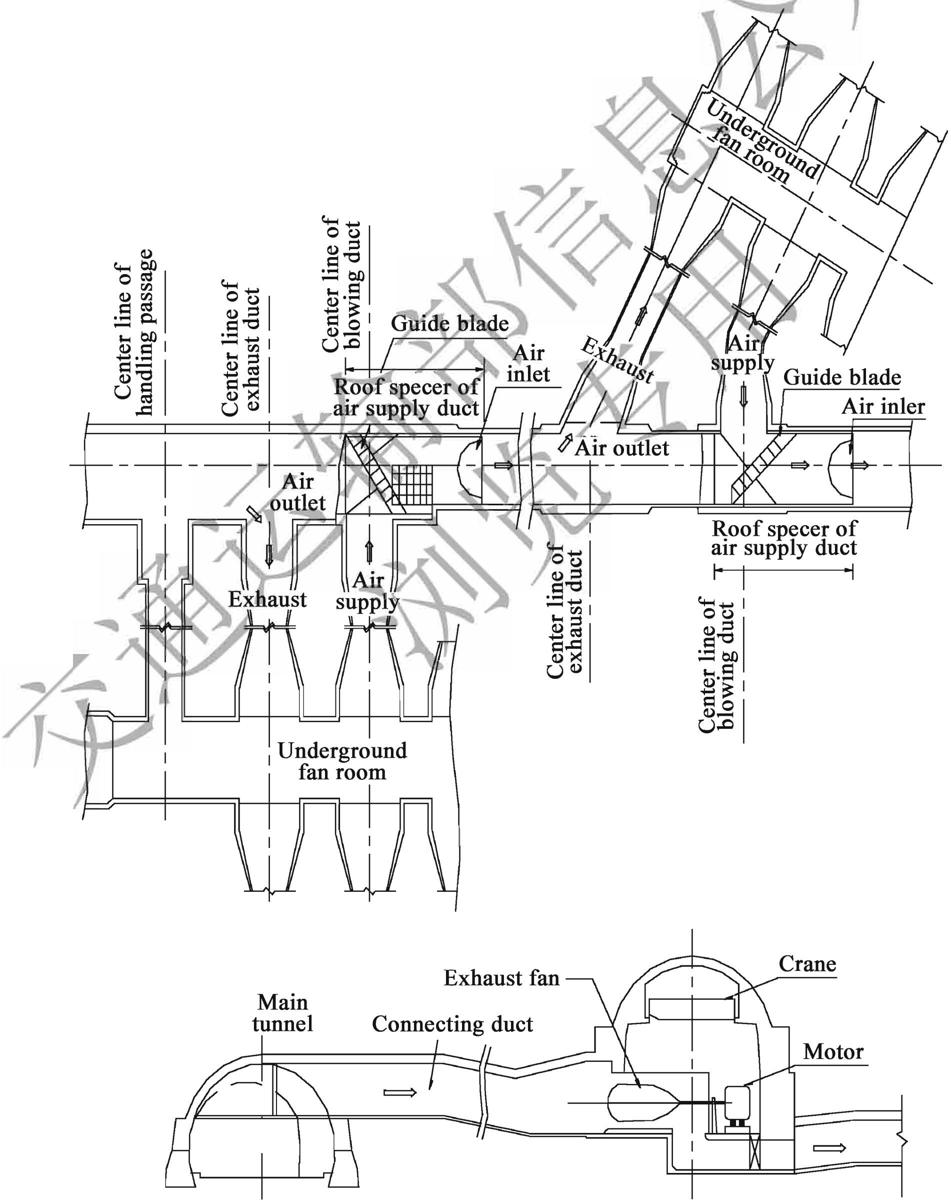


Figure 9-3　Case of underground fan room

9.3.2 The position relationship between underground fan room and tunnel may be determined according to the geological condition, and the position relationship among tunnel, ventilation shaft and connecting duct.

9.3.3 The layout of underground fan room shall meet the requirements of comprehensive arrangement, transportation, installation and overhaul of fans and their supporting facilities; and fans should be arranged in a centralized manner.

9.3.4 Large equipment transportation passage and escape passage shall be built between underground fan room and tunnel. Fire door shall be equipped in these passages; and maintenance path shall be built between underground fan room and connecting duct.

9.3.5 The ventilation design of highway tunnel shall include the design of ventilation, moisture protection, dust prevention, noise reduction and temperature regulation of underground fan room.

Background:
The heat generated by equipment operation will cause temperature rise in underground fan room, and the ambient humidity of underground space is high, which will adversely affect the operation of equipment in fan room and the management personnel. Therefore, ventilation, air conditioning and other systems may be used to adjust and control the air quality and noise in fan room to meet the physiological and psychological requirements of the personnel and the need of normal operation of equipment.

9.4 Ventilation shaft

9.4.1 The tunnel ventilation vertical shaft, inclined shaft and parallel pilot tunnel may be arranged separately or selected and used in combination.

9.4.2 The ventilation shaft arrangement scheme shall be compared by considering such factors as tunnel ventilation zone, size of ventilation shaft project, vertical and horizontal alignments of tunnel, engineering and hydrogeological conditions, terrain and landform, construction and operating conditions.

9.4.3 The ventilation shaft shall be placed in the place with a better geological condition, and shall avoid crossing the section with adverse climatic or geological conditions such as fault rupture zones, coal seam and water inrushes.

9.4.4 The ventilation shaft opening should be placed in the flat and open area with a good diffusion effect. The ventilation shaft opening elevation shall be at least 0.5m above that at the design flood frequency of 1/100.

Background:

The ventilation shaftopening should be placed in the flat and open area with a good diffusion effect for the convenience of shaft construction and building arrangement; and it is necessary to survey the engineering geological and hydrogeological conditions around the shaft to avoid the potential safety hazards caused by landslide and flood to ventilation system and operation of tunnel.

9.4.5 The smoke exhaust shaft shall not be used as an escape passage in case of fire.

9.4.6 The design air velocity of ventilation shaft should be 13.0 ~ 20.0m/s.

Background:

The design air velocity of ventilation shaft will directly affect the section size of ventilation shaft, thus the initial project investment will be greatly affected accordingly. The air velocity value of ventilation shaft is inversely proportional to its section size. Smaller section of ventilation shaft is conducive to saving project investment, but larger air velocity of ventilation shaft will increase the installed motor power of ventilation system fan, resulting in an increase in long-term operation cost of ventilation system. Therefore, according to domestic and overseas technical data, application of engineering and research result, the design air velocity of ventilation shaft is economical and reasonable in the range of 13.0 ~ 20.0m/s.

9.4.7 A shaft cap should be installed at the top of ventilation shaft to prevent rain and snow from entering; measures shall be taken in cold regions to prevent inside ventilation shaft and shaft mouth from icing up.

9.4.8 ~ The ventilation vertical shaft design shall meet the following requirements:

1 The shaft depth should not exceed 300m; if it exceeds 300m, a special demonstration shall be considered based on alignment selection, construction safety and project cost.

2 Theinner profile of vertical shaft should be in the form of circular section.

9.4.9 The ventilation inclined shaft design shall meet the following requirements:

1 The shaft depth should not exceed 1,000m; if it exceeds 1,000m, a demonstration shall be considered based on alignment selection, construction safety and project cost.

2 When the shaft length is not more than 700m, the design air velocity in inclined shaft may be 16.0 ~ 20.0m/s; when the shaft length is greater than 700m, the design air velocity in inclined shaft may be 13.0 ~ 16.0m/s.

3 The inclination angle of inclined shaft shall be determined according to the lifting method of inclined shaft construction. The angle should not be greater than 35° inbucket conveyor lifting, the angle should not be greater than 25° in trolley lifting, the angle should not be greater than 15° in belt conveyor lifting, and the angle should not be greater than 12° in trackless transportation.

9.4.10 The combined construction of air supply shaft and exhaust shaft shall meet the following requirements:

1 When air supply shaft and exhaust shaft are jointly built, the ventilation shaft shall be separated according to the respective clearance area required for air supply volume and exhaust volume of tunnel.

2 When air supply shaft and exhaust shaft of different ventilation zones of the tunnel are jointly built, the ventilation shaft shall be separated according to the respective clearance area required for air supply volume or exhaust volume of different ventilation zones.

Background:

In order to ensure the reliability and stability of the ventilation system of left and right tubes, when air supply shafts or exhaust shafts of different ventilation zones of the tunnel are jointly built, it is necessary to divide separate ventilation shaft spaces according to the respective clearance area required for air supply volume or exhaust volume of different ventilation zones.

If the air supply shafts or exhaust shafts of different ventilation zones share the same ventilation space, two ventilation systems not strongly correlated will establish a strong parallel relationship, and the start-up of the ventilation system of left tube (or right tube) will affect the ventilation system of right tube (or left tube). Once the design or operation management is unreasonable, they may be the resistance of each other and the ventilation effect thus will be affected.

9.4.11 The design of parallel pilot tunnel shall meet the following requirements:

1 The design schemes of parallel pilot tunnel should be compared by considering alignment selection, ventilation effect, project cost, operation cost, maintenance management and escape and rescue contingency plan in case of fire.

2 The design air velocity of parallel pilot tunnel may be 13.0 ~ 20.0m/s; when the parallel pilot tunnel becomesan escape and rescue passage, the design air velocity should not be greater than 7.0m/s.

9.5 Ventilation tower

9.5.1 When aboveground fan room is adopted, fresh air should be blown into ventilation shaft and polluted air be discharged from tunnel through ventilation tower. The ventilation tower should be located near ventilation shaft opening.

9.5.2 The air inlet of ventilation tower should be placed in the upwind direction, and the air outlet should be placed in the downwind direction; and the ventilation tower in mountain should face the open area.

9.5.3 The elevation of air outlet of ventilation tower shall be higher than that of air inlet, and the height difference shall not be less than 5m; the planar spacing between air inlet and air outlet shall not be less than 5m; air inlet and air outlet shall not be placed in the same direction to avoid bypass flow.

Background:
This Clause is hereby stipulated in order to prevent the exhaust from polluting air supply.

9.5.4 The height from air inlet bottom to ground should not be less than 2m; when air inlet is in a preferable green area, the distance from air inlet to ground may be appropriately reduced, but shall not be less than 1m.

9.5.5 The air velocity of air supply tower should not exceed 8.0m/s, and that of exhaust tower should not exceed 15.0m/s.

Background:
9.5.4 ~ 9.5.5 The ventilation tower is a facility connected to the outside that discharges polluted air and blows in fresh air in tunnel, and affects the operation effect of tunnel ventilation system. The location of ventilation tower and the tower air velocity in this Clause shall refer to relevant provisions of the current *Code for Design of Metro* (GB 50157).

This Clause is hereby stipulated in order to prevent the air supply system from dust and debris near the air inlet.

9.5.6 Safety precautions shall be taken for ventilation tower to prevent human and animal from entering; and tower hood shall be used to prevent rain and snow from entering.

***Background*:**

The safety protection design of ventilation tower is to prevent foreign matters such as animal and garbage from entering tower and damaging equipment, and personnel from falling.

9.5.7 The ventilation diffusion of ventilation tower may be calculated by following formula:

1 The effective height of the air outlet of ventilation tower may refer to Figure 9.5.7 and be calculated according to formula (9.5.7-1); the structure form of air outlet and the exhaust rising effect may refer to Table 9.5.7.

$$H_e = H_0 + \Delta H \tag{9.5.7-1}$$

$$\Delta H = \frac{3.1005}{1 + 0.43 \times \frac{v}{v_g}} \cdot \frac{\sqrt{Q_e \cdot v_g}}{v} \tag{9.5.7-2}$$

Where:

H_e—effective height of air outlet (m);

H_0—structure height of air outlet (m);

ΔH— rising height of exhaust (m);

Q_e—exhaust volume (m^3/s);

v_g—air velocity of the air outlet of ventilation tower (m/s);

v—average atmospheric air velocity (m/s).

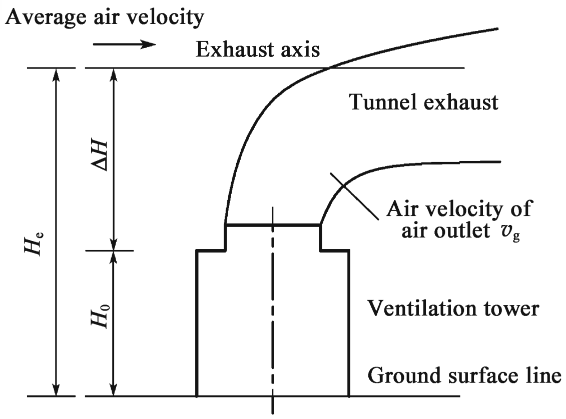


Figure 9.5.7 Effective height of air outlet

Table 9.5.7 Structure form of air outlet and exhaust rising effect of ventilation tower

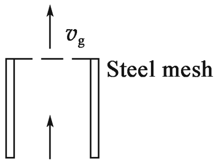
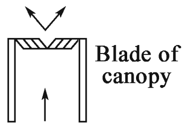
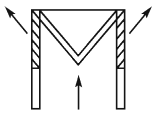
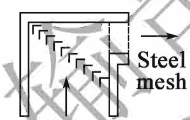
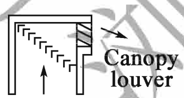
Form of air outlet			Exhaust rising effect
Upward air supply	A		The structure is basically the same as the factory chimney, and its discharge velocity may effectively change rising height.
	B		The exhaust direction becomes sidelong due to the blade, which is unfavorable to the change of rising height.
	C		The same as B

Table 9.5.7 (Cont'd)

Form ofair outlet			Exhaust rising effect
Sideway air supply	D		The discharge velocity cannot decide rising height.
	E		Since blades are facing downward, discharge velocity lowers down exhaust height, which is an unfavorable form.

2 The concentration of pollutants discharged from tunnel by exhaust tower ($z=0$) may be calculated according to formula (9.5.7-3):

$$C(x,y,0)=\frac{q}{\pi\cdot\sigma_y\cdot\sigma_z\cdot v}\cdot\exp\left[-\left(\frac{H_e^2}{2\sigma_z^2}+\frac{y^2}{2\sigma_y^2}\right)\right] \qquad (9.5.7\text{-}3)$$

Where:

C—concentration (cm^3/m^3);

x—downwind direction calculation point coordinates (m);

y—horizontal coordinates of calculation point (m);

q—source strength (ml/s)

σ_y, σ_z—horizontal and vertical diffusion width (m);

H_e—effective height of air outlet (m);

v—average air velocity (m/s).

Background:

The calculation method for pollutant diffusion of ventilation tower herein shall refer to the smoke exhaust mode of factory chimney. It is assumed that the pollution concentration of the gas diffused is normally distributed, and the diffusion calculation formula is a normal diffusion one. The formula takes exhaust source (center of the air outlet) as origin, wind direction as x-axis, horizontal direction as y-axis and vertical direction as z-axis. For ground surface concentration calculation, $z = 0$. In the formula, the diffusion width is closely related to many factors such as atmospheric stability and surface roughness.

10 Smoke Prevention and Extraction in Case of Tunnel Fire

10.1 General

10.1.1 Mechanical fire smoke prevention and extraction systems shall be provided for the highway and Class-I highway tunnel with a $L > 1000$m and the Class-Ⅱ, Class-Ⅲ and Class-Ⅳ highway tunnels with a $L > 2,000$m.

***Background*:**

According to project practices in China, the highway and Class-Ⅰ highway tunnel with a $L \leqslant 500$m and the Class-Ⅱ highway tunnel with a length of $500\text{m} < L \leqslant 1,000$m don't need the mechanical fire smoke prevention and extraction systems.

The installation of mechanical ventilation for hazard prevention and smoke extraction for the highway and Class-Ⅰ highway tunnel with a length of $500\text{m} < L \leqslant 1000$m and the Class-Ⅱ highway tunnel with a length of $1,000\text{m} < L \leqslant 2,000$m is related to the geometric conditions of tunnel (length and longitudinal grade), traffic conditions (mode of transport, traffic volume, traffic composition and driving speed) and pedestrians and meteorological conditions. For example, for the tunnel at LOS 3 or 4 in a long term and the tunnel with an average longitudinal grade of $\leqslant -3.0\%$, the mechanical smoke prevention and extraction systems are installed generally to ensure traffic safety according to survey summary.

10.1.2 The highway tunnel smoke prevention and exhaust shall be designed by considering tunnel length, traffic volume, traffic composition, section size, horizontal curve radius, longitudinal grade, traffic condition, escape condition, natural condition and fire hazard.

***Background*:**

The damage and impact caused by highway tunnel fire are large, which makes the rescue difficult.

Especially for long tunnel and extra-long tunnel, the fire smoke prevention and extraction is an important part of ventilation design.

The longer the tunnel, the larger the traffic volume and the greater the probability of fire; the longitudinal grade and traffic condition will affect the size of ventilation system, and also the organization of smoke extraction and ventilation; the tunnel fire load mainly depends on the type and quantity of combustibles on vehicle. Therefore, in the design of highway tunnel smoke prevention and extraction, factors such as tunnel length, traffic volume, traffic composition, section size, horizontal curve radius, longitudinal grade and traffic condition shall be considered.

Tunnel is narrow and long. It would be more like an enclosed space if it is longer. When a fire occurs, the amount of smoke in tunnel is large, and it is in poor visibility, the heat dissipation is slow, and the temperature is high. After tunnel fire, it is difficult to carry out safe evacuation, which would easily cause traffic congestion and the secondary disasters. When a fire occurs in a bi-directional tunnel, a single-tubeuni-directional tunnel or a tunnel with high traffic flow or at peak hour, the poor visibility and limited evacuation passages, and drivers' fear of smoke and fire will easily cause traffic congestion or new traffic accident because of hurry and confusion, thus it would be more likely to cause the secondary disasters. When a fire occurs, the traffic air in tunnel will drastically decrease. In addition to the hot pressure generated by fire, the natural wind has a great impact on ventilation and smoke extraction in tunnel. Therefore, in the design of highway tunnel smoke prevention and extraction, factors such as escape conditions, natural condition and fire hazard must be considered.

10.1.3 The highway tunnel fire smoke extraction should be considered as if one fire occurs at the same time in one tunnel.

***Background*:**
The fire ventilation and smoke extraction of the same tunnel is considered as if only one fire occurs at the same time. It is determined according to the experience of construction and operation of highway tunnels in China and with reference to the requirements of China's construction and metro standards and foreign standards related. For example, there's similar provision in the *Specifications for Fire Protection Design of Buildings* (GB 50016-2006) that "the amount of fire water shall be calculated according to the duration of fire and one fire at the same time in the tunnel…"

10.1.4 The highway tunnel fire smoke extraction method shall give comprehensive consideration to technical difficulty, project cost, operation and maintenance and smoke extraction effect of various methods, and be determined by technical and economical comparison.

Background:

Generally, the tunnel fire smoke extraction mode is related to the operation and ventilation mode of tunnel. The selection of operation and ventilation mode of tunnel is related to technical difficulty, project cost, operation and maintenance, and smoke extraction effect of ventilation system. The safety and economy of fire smoke extraction method is determined by technical and economical comparison.

10.1.5 The design of highway tunnel fire smoke prevention and extraction shall follow the following principles:

1 The highway tunnel fire smoke prevention and extraction systems should be used in cooperation with routine operational ventilation system.

2 It shall be beneficial to personnel evacuation and prevent fire smoke from intrudingcross-passages for pedestrians and vehicles, adjacent tunnels or parallel pilot tunnels and ancillary buildings.

3 It shall be able to effectively control the diffusion of fire smoke.

4 It shall be conducive to rescuing and firefighting.

Background:

Subject to the principle of safety, applicability and economic rationality, the ventilation system is usually designed to be a combined system for ventilation and air exchange under normal condition and smoke extraction in case of fire. The setting of smoke extraction system is closely related to the smoke extraction mode and routine operational ventilation mode of highway tunnel. For example, the highway tunnel withlongitudinal ventilation with full jet stream and smoke extraction mode combines the common duct (i.e., lane space) and fans.

The cross-passages for pedestrians and vehicles, adjacent tunnels or parallel pilot tunnels and the guarded ancillary buildings in tunnel are places to ensure safe evacuation and rescue and shall be protected from smoke in case of tunnel fire, thus smoke prevention design shall be made.

10.1.6 The highway tunnel fire smoke extraction design shall be considered in combination with the escape and shelter facilities and ventilation control.

Background:

The setting of smoke extraction system and escape and rescue facilities is subject to the principle of ensuring the safety of personnel and facilitating personnel evacuation, and the size of smoke extraction system is related to escape and shelter facilities.

10.1.7 Facilities with smoke prevention systems by mechanical pressurization shall be provided for the following places in highway tunnels:

1 special refuge or evacuation passages and its front room;

2 independent refuge room;

3 ancillary buildings that cannot be dismantled temporarily in case of fire.

Background:
In order to ensure safe evacuation of personnel in ancillary buildings and other special refuge or evacuation passages, the places that are provided with mechanical pressurized smoke prevention system are determined according to different natures and requirements of use and the general principles established in smoke prevention and extraction design based on China's current technical standard for engineering construction and fire protection.

10.1.8 The ancillary buildings of tunnel shall be provided with mechanical smoke extraction system.

10.1.9 The tunnel's cross-passage gate shall be able to prevent fire and smoke and be wind-pressure-resistant.

Background:
Cross-passage is an important passage as a temporary shelter for people and vehicles and for safe evacuation in case of fire, hence it must be protected from smoke when a tunnel fire occurs. Under the action of piston effect of traffic or mechanical ventilation, a certain air pressure will form in the cross-passage, thus this Clause is hereby made.

10.2 Smoke extraction in case of tunnel fire

10.2.1 The maximum heat release rate in case of tunnel fire shall be determined by Table 10.2.1.

Table 10.2.1 The maximum heat release rate (MW) in case of tunnel fire

Mode of transport	Tunnel length	Highway class		
		Expressway	Class-Ⅰ highway	Class-Ⅱ, Class-Ⅲ and Class-Ⅳ highway
Uni-directional traffic	$L > 5,000$m	30	30	—
	1,000m $< L \leq 5,000$m	20	20	—
Bi-directional traffic	$L > 4,000$m	—	—	20
	2,000m $< L \leq 4,000$m	—	—	20

Note: The maximum heat release rate in case of a fire in special tunnels such as coal passage and passenger car passage should be determined according to actual condition.

***Background*:**

The *Guidelines*, in combination with the actual situation of serious safety hazards in highway tunnel in China, refers to the literatures cited in Technical Report 2007 of PIARC, and considers such factors as highway class, tunnel length, mode of transport (uni-directional or bi-directional), tunnel site (mountain or underwater), and puts forward the specified values as shown in Table 10.2.1. Since the traffic volume is closely related to highway class, therefore the indicator of traffic volume is not stated.

10.2.2 For the highway tunnel that extracts smoke longitudinally, the required air volume flow for fire smoke extraction may be calculated according to formula (10.2.2):

$$Q_{req(f)} = A_r \cdot v_c \quad (10.2.2)$$

Where:

$Q_{req(f)}$—required air volume flow for tunnel fire smoke extraction (m^3/s);

A_r—tunnel clearance area (m^2);

v_c—critical velocity in tunnel fire (m/s).

***Background*:**

The minimum air velocity that can stop smoke reflux in case of a tunnel fire is called criticalvelocity. Critical velocity is one of key parameters of tunnel smoke extraction system design.

10.2.3 For the highway tunnel with full transverse, semi-transverse and centralized smoke extraction, the smoke production rate in case of fire may refer to Table 10.2.3.

Table 10.2.3 Smoke production rate in case of a fire in the tunnel with full transverse, semi-transverse and centralized smoke extraction

Heat release rate (MW) in case of fire	20	30	50
Smoke production rate (m^3/s)	50 ~ 60	60 ~ 80	80 ~ 100

Background:

For the tunnel withfull transverse, semi-transverse and centralized smoke extraction, the required air volume flow for tunnel fire smoke extraction is related to smoke production rate, sectional area of tunnel and longitudinal air velocity. The smoke production rate herein refers to the technical data from the Permanent International Association of Road Congress (PIARC) and the Europe.

10.2.4 The highway tunnel fie smoke extraction design shall consider the effect of fire-induced thermal pressure, which may be calculated by formula (10.2.4-1) and (10.2.4-2):

$$\Delta P_f = \rho \cdot g \cdot \Delta H_f \cdot \frac{\Delta T_x}{T} \quad (10.2.4\text{-}1)$$

$$\Delta T_x = \Delta T_0 \cdot e^{-\frac{c}{G}x} \quad (10.2.4\text{-}2)$$

Where:

ΔP_f— fire-induced thermal pressure (N/m^2);

ρ—ambient air density at ventilation calculation point (kg/m^3);

g—gravitational acceleration, 9.8m/s^2;

ΔH_f—elevation difference of high-temperature gas through tunnel (m);

T—average absolute temperature of air when high-temperature gas flows through tunnel after fire (K);

x—distance from calculation point of smoke temperature rise to fire source point along smoke flow direction (m);

ΔT_x—air temperature increment at a distance of × meters from fire source along smoke flow direction (K);

ΔT_0—air temperature increment at fire source before and after fire (K);

G—mass flow of fire smoke at x(m) along smoke flow direction (kg/s);

c—coefficient, $c = \frac{k \cdot C_r}{3600 C_p}$;

C_r—perimeter of tunnel section (m);

K—thermal conductivity of rock, $k = 2 + k' \cdot \sqrt{v_1}$, k' is 5 ~ 10, and R is smoke velocity (m/s);

C_p—constant-pressure specific heat capacity of air, 1.012 kJ / (kg · K).

Background:

The additional hot air pressure that occurs in a tunnel fire is calledfire-induced thermal pressure or resistance of smoke flow due to buoyancy effect. The fire-induced thermal pressure is the increment in natural air pressure caused by change of fire smoke. The direction of fire-induced thermal pressure in fire smoke area is denoted as positive along the uphill direction of tunnel and negative in the downhill direction. The fire-induced thermal pressure changes constantly with the diffusion of high-temperature smoke.

10.2.5 For the highway tunnel that extracts smoke longitudinally, the critical velocity in fire may refer to Table 10.2.5.

Table 10.2.5 Critical velocity in fire v_c

Heat release rate (MW)	20	30	50
Critical velocity in fire v_c (m/s)	2.0 ~ 3.0	3.0 ~ 4.0	4.0 ~ 5.0

***Background*:**

The tunnel fire smoke extraction system is mainly used to control the flow direction of fire smoke in tunnel and effectively discharge it from tunnel. For the tunnel that extracts smoke longitudinally, when a fire occurs in tunnel, the smoke is discharged through tunnel exit or nearest smoke air outlet.

For the tunnel that extracts smoke longitudinally, the air velocity in tunnel will cause smoke turbulence, which will affect the stratification in the downstream of fire. The greater the air velocity, the more obvious the turbulence is. Besides, the stratification will also be disturbed by the longitudinal grade of tunnel and vehicles. The use of critical velocity to control the flow of smoke can not only prevent smoke reflux from endangering vehicles and people blocked in the upstream of fire, but also prolong the stay time of smoke on the top wall of tunnel to prevent the smoke from spreading downstream, thus increasing the escape time of people. The critical velocity depends on the heat release rate in fire, sectional area of tunnel and tunnel clearance height. The *Guidelines* generally refers to the recommendations from the PIARC.

10.2.6 The design of fire smoke extraction for the single-tube bi-directional tunnel with longitudinal smoke extraction shall follow the following principles:

1 The smoke extraction direction and smoke extraction speed in tunnel shall be determined according to fire location, traffic condition, natural smoke extraction condition and ventilation shaft setting, and the stroke of smoke in tunnel shall be shortened.

2 The maximum stroke of fire smoke in tunnel should not exceed 3,000m.

3 During the safe evacuation, the longitudinal smoke extraction speed shall not exceed 0.5m/s.

4 During the firefighting rescue, the longitudinal smoke extraction speed shall not be smaller than the critical velocity in fire.

Background:

1 According to the conclusion of tunnel fire test, obvious smoke-air stratification will take shape within a range of 700m in the upwind and downwind direction of vertical smoke flow in 8 ~ 10min after fire, and the high-temperature smoke mainly gathers at the arch crown. In order to ensure that the smoke-air stratification is not destroyed in the safe evacuation, the airflow velocity near the origin of fire should not be too high. Therefore, during the safe evacuation, the smoke extraction speed shall not exceed 0.5m/s.

2 When the air velocity in tunnel is greater than the critical velocity in fire, the smoke flows in one direction longitudinally along tunnel, and the temperature of the smoke in the downwind direction is much higher than that in the upwind direction. Therefore, during the firefighting and rescue, in order to enable the firefighters to safely arrive at the fire scene from the upwind direction of the smoke in tunnel, the longitudinal smoke extraction speed shall not be smaller than the critical velocity in fire.

10.2.7 The design of fire smoke extraction for the uni-directional tunnel with longitudinal smoke extraction shall follow the following principles:

1 The direction of smoke extraction in tunnel shall be the same as driving direction and the smoke shall be discharged through tunnel exit or nearest smoke air outlet.

2 The maximum stroke of fire smoke in tunnel should not exceed 5,000m.

3 The longitudinal smoke extraction speed shall not be smaller than the critical velocity in fire.

4 The fireproof shutter and fireproofgate of cross-passage in the downwind of the origin of fire shall be closed.

Background:

1 In the event of a fire in theuni-directional tunnel, the longitudinal smoke extraction speed shall refer to the principle of preventing smoke from reflux, in order to ensure there is no fire smoke in the upstream of the origin of fire, which is beneficial to the evacuation of people through cross-passage and vehicle entrance of tunnel, and safe leaving of motor vehicles in the downstream of the origin of fire from tunnel. Therefore, the direction of smoke extraction shall be consistent with that of the tunnel traffic flow.

2 The direction of smoke extraction in the uni-directional tunnel is consistent with driving direction. In order to prevent the smoke in the downstream of the origin of fire from spreading

through cross-passage to another tunnel, the fireproof shutter and fireproof gate of cross-passage in the downwind of the origin of fire shall be closed.

10.2.8 The design of fire smoke extraction for the highway tunnel with smoke duct for centralized smoke extraction shall follow the following principles:

1 The longitudinal air velocity in tunnel should not exceed 2.0m/s; the smoke extraction zone shall be free from smoke reflux.

2 The smoke extraction zone may be divided according to tunnel ventilation zone, and the length of each smoke extraction zone shall not exceed 1,000m.

3 The tunnel that is transversely ventilated and semi-transversely ventilated shall exhaust smoke throughmain duct; the spreading length of smoke in the tunnel should not exceed 300m.

4 Thesmoke vent shall be placed in each smoke extraction zone, and the vertical spacing of vents should not be less than 60m.

5 The smoke in tunnel shall be discharged through the smoke vent arranged longitudinally along tunnel. The smoke vent shall be placed on the top of tunnel or the upper part of side wall; and the smoke vent may be placed independently or combined with the air outlet.

6 When thefull transverse ventilation system is converted into a smoke extraction system, the supply of fresh air near the origin of fire shall be stopped; and the tunnel air supply semi-transverse system shall be converted into an exhausting semi-transverse system for smoke extraction.

Background:

For the highway tunnel with smoke duct for centralized smoke extraction, the fire smoke is discharged from tunnel through smoke vent on the top of tunnel or the upper part of side wall, to ensure the stranded people stay in a smoke-free environment.

According to the observation report of Japanese measurement test, in order to achieve the above purpose, the longitudinal smoke extraction speed must be smaller than 2.0m/s. When the longitudinal air velocity in tunnel is large, vertical turbulence will happen in the shear layer between smoke and fresh air, and the upper smoke will be rapidly cooled, to mix the smoke on the whole tunnel section. However, if the longitudinal air velocity in tunnel is zero, within 10min after the fire, the smoke will spread to both sides of the origin of fire in a manner of stratification, thus causing harm to the stranded drivers and passengers in tunnel. According to relevant Chinese and foreign information, the design requirements of fire smoke extraction are proposed.

10.2.9 The design air velocity in smoke duct should not exceed 15.0m/s, and the design air velocity at the smoke vent should not exceed 10.0m/s.

Background:
The requirements on design air velocity of smoke vent and smoke duct are proposed according to relevant Chinese and foreign information.

10.3 Tunnel smoke ventilator

10.3.1 The tunnel smoke ventilator shall comply with the following requirements:

1 The continuous normal running time of the tunnel smoke ventilator at the temperature of 250℃ shall not be less than 60min; and the smoke ventilator silencer shall keep stable performance in the smoke at the temperature of 250℃.

2 Tunnel smoke ventilator shall have a standby fan.

3 The reversible fan shall be able to fulfill reverse operation within 90s.

Background:
For the high temperature resistance requirements of fan motor that has direct contact with the high temperature smoke, this Clause refers to the requirement that "it shall work properly for at least 60min in smoke at the temperature of 250℃" stipulated in *High Temperature-Resistant Test Methods for Smoke Ventilators* (GA 211-2009).

In order to ensure the normal use of fan silencer under the action of fire and high temperature, the requirement of high temperature resistance is put forward.

10.4 Smoke prevention of escape passage and shelter

10.4.1 The excessive pressure of the front room of special evacuation passage and independent shelter shall not be less than 30Pa, and that of special evacuation passage and independent shelter shall not be less than 50Pa.

10.4.2 The smoke prevention design of special shelter and evacuation passage shall be based on its length and clearance, and a reasonable and applicable mechanical positive ventilation mode shall be selected; the air supply volume of front room and the size of air inlet shall be determined and calculated by the air velocity not less than 1.2m/s at the entrance.

10.4.3 The pressurized air supply volume for the smoke prevention design of independent shelter shall be calculated according to the ground area not less than 30m^3/h per square meter, and the time to supply fresh air shall not be less than the duration of fire.

10.4.4 The air inlet of mechanical pressurized air supply and smoke prevention system shall be close to or face the evacuation passage and the entrance of shelter and the air velocity should not exceed 7.0m/s.

Background:

10.4.1 ~ 10.4.4 The mechanical pressurized air supply system keeps a certain positive pressure in independent shelter, to prevent high temperature smoke from entering and provide fresh air for evacuees. The design regulations for mechanical pressurized air supply volume, fresh air supply time and exhaust facilities of independent shelter are proposed according to the *Specifications for Fire Protection Design of Buildings* (GB 50016) and *Code for Design of Heating and Ventilation and Air Conditioning* (GB 50019).

10.5 Smoke prevention and extraction of ancillary buildings

10.5.1 The underground fan room shall be provided with independent mechanical smoke prevention and extraction system.

10.5.2 The mechanical smoke extraction system and ventilation and air-conditioning system of ancillary buildings in tunnel should be separated; when they are combined, reliable fire safety measures shall be taken for ventilation and air-conditioning system and they shall be capable of quick switching under accident condition.

Background:

The tunnel ancillary buildings include tunnel operation management center (station), central control room (station), fan room, substation inside and outside the tunnel, water pump house and others. The smoke prevention and extraction design of tunnel ancillary buildings is mainly in the scope of architectural design and may be implemented with reference to the current *Specifications for Fire Protection Design of Buildings* (GB 50016).

11 Fan Selection and Layout

11.1 General

11.1.1 The highway tunnel ventilation can be achieved by mechanical equipment such as jet fan, axial fan, centrifugal fan and dust collector.

Background:

The jet fan is a axial fan with fixed parameters, which can be classified intouni-directional jet fan and bi-directional reversible jet fan according to the working mode.

The ventilation of the extra-long tunnel with a length over 5,000m generally adopts axial fan with a large air volumeflow and a low air pressure. However, when the full air pressure of exhaust fan reaches 5,000N/m^2, it shall be selected between axial fan and centrifugal fan by comparison. In general, the axial fan has the advantages of small size, high adaptability with civil construction, high efficiency and convenient reversing of fire smoke extraction, but it costs more and makes much more noise.

There are physical, chemical and biological dust collectors, and the physical dust collector includes dust filter and electrostatic dust collector; and China begins to produce chemical and biological dust collectors such assoil-based biofilter system. The electrostatic duct collector removes the particulate matters in air by means of static electricity, so as to improve the environment inside the tunnel and ensure safe driving. This equipment is very conducive to energy conservation and environment protection.

11.1.2 The fan shall meet the use requirements of tunnel ventilation system and is energy-efficient and environmentally friendly.

11.2 Selection and layout of jet fan

11.2.1 The selection of jet fan shall meet the following requirements:

1 The jet fan shall be the fan with silencer exclusive for highway tunnel.

2 The selection of jet fan shallrefer to the diameter of different types of jet fan, installed motor power of a single jet fan, total installed power of fans in tunnel, and long-term operation cost.

3 Theuni-directional fan should be used for uni-directional tunnels; while the bi-directional fan shall be used for bi-directional tunnels, and the fan model of the same tunnel should be the same.

4 The air volumeflow and thrust of the bi-directional reversible jet fan in reverse rotation should not be lower than 98% of that in forward rotation; the reverse air volume flow of the uni-directional jet fan in reverse running should be 50% ~70% of the air volume flow in forward rotation.

5 When a fire occurs in tunnel, jet fan shall be able to work normally for 60min at an ambient temperature of 250℃.

6 The A-sound level of jet fan shall be less than 77dB when the measurement is conducted 10m away from fan outlet and at an angle of 45°.

7 The ingress of protection of jet fan motor shall not be lower than IP55, and its insulation grade shall not be lower than grade F.

8 Under the rated working condition, the overall design service life of fan shall not be less than 20 years, and the safe running time before the first overhaul shall not be less than 18,000h.

Background:

1 Under the same condition, the uni-directional fan has a higher ventilation efficiency than the bi-directional fan; for uni-directional tunnel, regardless of the routine operation or fire and smoke prevention, the fan running direction is generally consistent with traffic direction. Therefore, it's better for the uni-directional tunnel to choose the uni-directional fan. Since the uni-

directional fan can also run reversely, the ventilation system needs to be reversed on rare occasions, the jet fan can also provide a certain air volume flow and pressure rise. For bi-directional tunnel, the direction of ventilation in tunnel may be adjusted as the change of traffic condition. Therefore, the bi-directional fan is selected for bi-directional tunnel. In order to facilitate engineering construction and long-term operation management, in general, the jet fan model shall be the same for the same tunnel.

2 Under the rated working condition, the overall design service life of fan shall not be less than 20 years, except for vulnerable parts such as anti-corrosion layer of the outer surface of fan, motor and electrical wiring.

11.2.2 The layout of jet fan on tunnel section shall meet the following requirements:

1 The jet fan shall not intrude into tunnel clearance profile, and the net distance between the edge of jet fan and the tunnel clearance profile should not be less than 15cm.

2 It should be fixed or suspended; when recessed installation is adopted, the transition design of tunnel structure shall be noticed, and the guide blades may be placed at the air inlet and air outlet of fan.

3 The number of fans on the same section shall be determined according to the shape of tunnel section, section size and overall layout of the full-tunnel jet fans and the rationality of power distribution system implementation.

4 When 2 or more jet fans are placed on the same section, the net distance between two adjacent fans should not be less than once the diameter of fan impeller; and the fan model on the section shall be the same.

Background:

1 In tunnel, the installation of equipment shall not intrude into tunnel clearance profile; especially the installation of jet fan shall have sufficient space. According to surveys, it is common that vehicles go beyond limit height due to various reasons in China. In view of the fact that the mass of jet fan is generally more than 500kg and is installed at tunnel arch, once it is hit by a vehicle, it will bring serious safety hazard.

In view of this, when the jet fan is suspended at arch crown, the net distance from the lower edge of the jet fan and the tunnel clearance profile should not be less than 15cm; when side wall mounted or recessed installation is adopted, the net distance from the left and right edge of jet fan to the tunnel clearance profile should not be less than 15cm.

2 Generally, 2 jet fans are placed on the same section of two-lane tunnel; and the number of jet fans on the same section of three-lane and four-lane tunnel shall be determined according to the section size and the arrangement of lightings.

11.2.3 The layout of jet fan in the longitudinal direction of tunnel shall meet the following requirements:

1 The location of jet fan shall be determined by giving consideration to the ventilation requirements of tunnel operation, fire smoke prevention and extraction, and the rationality of fan power supply and distribution facilities.

2 The spacing between jet fans with a diameter of no more than 1,000mm should be less than 120m, and the spacing between jet fans with a diameter greater than 1,000mm should be greater than 150m.

3 For the straight tunnel with a length not more than 3,000m, the jet fan may be placed at theopening zone on both ends; the jet fan of extra-long tunnel should be placed at the opening zone on both ends and at least 3 zones in the middle part of tunnel; and for the curve tunnel with a length greater than 2,000m, the jet fan should be placed at the curve zone.

4 When theuni-directional tunnel uses external substation for centralized power supply to the jet fans in tunnel, the distance between the first set of fans at entrance zone and the mouth should be 100m.

5 The jet fan and other mechanical andelectrical equipment should not interfere with each other. The built-in elements of fan should keep away from cross-passages for vehicles and pedestrians and lay-by.

6 The longitudinal arrangement distance of jet fan in tunnel's curve zone should not exceed l00m.

Background:

1 In terms of tunnel ventilation effect, it is ideal to place jet fans evenly in the whole tunnel. However, between the jet fan and its power supply and distribution facilities, the main investment is made for the power supply and distribution facilities; the farther the fan is from substation, the greater the voltage drop; and the larger the required cable diameter, the higher the material cost. When the tunnel operational ventilation effect and effective smoke prevention are archived, moderate centralized arrangement of jet fans is beneficial to reduce engineering

investment and long-term operation cost.

2 The jet lengths generated due to air pressurization by jet fans of different calibers are different. According to tests, the jet fan arrangement spacing specified herein can produce a better pressure rising effect.

3 The jet fan achieves ventilation by the high-speed airflow from its outlet to induce the air to reach a certain speed. According to a number of field tests of various projects, it takes some time, like 3 ~ 5min, from the opening of jet fan set to the achievement of a certain average air velocity in tunnel. Therefore, for extra-long tunnel, especially for the full jet stream ventilation system for disaster prevention, in order to improve the reliability and efficiency of ventilation system, jet fans should be arranged in multiple zones in tunnel.

4 According to actual measurement and experience, vehicles can bring in enough fresh air within the range about 200m from tunnel portal, thus jet fans may not be placed in this zone. But when theuni-directional tunnel uses external substation for centralized power supply to the jet fans in tunnel, once the distance between the first set of fans of entrance zone and the mouth is too large, the distribution cable length of each fan in this zone will increase, thus resulting in great waste. According to engineering experience, 100m would be more reasonable.

5 The tunnels with mechanical ventilation have many related mechanical andelectrical equipment in tunnel. The installation position of jet fans should keep away from fire hydrant cabinet, PLC control cabinet and other rooms; the high-speed airflow from the inlet and outlet of jet fan will shake camera; due to large size, the jet fan will cover lane indicator, real-time information board and other traffic monitoring equipment. Therefore, the positional relationship between the jet fan and other mechanical and electrical equipment should be coordinated to prevent them from mutual interference.

Besides, the arrangement of the jet fan incross-passage for vehicles and pedestrians has some structural difficulties; usually, the lay-by has end wall, which will generate a large local resistance to the high-speed airflow from the air outlet of jet fan, thus the ventilation effect of jet fan is greatly reduced. Therefore, this Clause is hereby made.

11.2.4 The following matters shall be noted in the installation of jet fans:

1 The forward running direction of fans shall be consistent with the main airflow direction of tunnel ventilation.

2 The structural bearing capacity to support fans shall not be less than 15 times of the actual

static load of fans, and theload test of supporting structure shall be conducted before installation of fans.

3 Fans shall be equipped with a safety chain and maintain proper slackness; when the safety chain is stressed, it shall be able to bear the static load of jet fans and their mounting bracket.

4 The installation parts and fastenings of fans shall be steel components, and the surface shall be anti-corrosive; the tunnels by the sea or with serious pollution and corrosion should be treated against salt-spray corrosion.

5 The installation parts and fastenings of fans may be welded or bolted with the built-in elements of supporting structure of fans. Vibration-reduction measures shall be taken between fan fastenings and the fan or between the built-in elements of fan's supporting structure.

6 The axis of fan shall be parallel to that of tunnel, and the error should not be greater than 5mm.

Background:

1 The actual static load of fan includes mounting bracket.

2 The purpose of safety chain is to help tunnel operation and management personnel to judge whether there's any potential safety hazard in the built-in elements and fastenings for suspension of jet fan according to the fact that whether the safety chain is stressed; besides, the safety chain is also an emergency safety device for suspension of jet fans.

3 The environment inside the tunnel is bad, and the oil contamination, dust and structural water leakage and penetration are extremely serious. Therefore, the installation fastenings of fans shall be steel components and anti-corrosive. For the tunnels by the sea or with highly corrosive materials, the metal parts in tunnel are more seriously corroded, thus the mounting bracket of jet fans may be made of stainless steel. If ordinary steel components are used, strict anti-corrosion treatment, such as hot-dip galvanizing and epoxy resin, must be carried out.

11.2.5 The operation of jet fan shall be in accordance with the following provisions:

1 The jet fan should be started in sets; when multiple sets of jet fans are required to operate at one time, they shall be started in a delayed manner.

2 In routine ventilation, the unit with the shortest cumulative running time shall be started first.

Background:

1 When multiple sets of jet fans are required to operate at one time, in order to avoid the impact of starting current on the power supply equipment of tunnel, they are started in a delayed manner.

2 In order to ensure the balanced operation of each unit (set) of jet fan, in routine ventilation, the unit with the shortest cumulative running time shall be given priority.

11.3 Selection, layout and air volumeflow adjustment of axial fan

11.3.1 The selection of axial fan shall meet the following requirements:

1 The fan characteristics shall be determined according to design requirements, and the selection of axial fan shallrefer to different installation locations and environmental conditions.

2 The axial fan with large air volume flow, low air pressure and rotatable stationary blade should be selected; the selection of fan model shall be in combination with the tunnel design air volume flow, air pressure, power and efficiency.

3 Before the completion of the civil works of ventilation system and before the installation of axial fan, the parameters of axial fan shall be verified in combination with the civil works condition and the performance of axial fan according to theresistance of ventilation system and the total pressure efficiency of fan.

4 The insulation grade of axial fan for fire extraction shall not be lower than grade F; while that of other axial fans shall not be lower than grade H; and the ingress of protection of axial fan shall not be lower than IP54.

Background:

The technical parameters of axial fan include air volume flow, total pressure, total pressure efficiency, motor power, rotate speed, voltage class, noise, diameter and limiting quality.

1 The highway tunnel axial fan is generally composed of impeller, case, current collector, cowling, blade, diffuser, flexible connection and air valve, and some axial fans have an

additional deflector. The axial fan is classified into horizontal and vertical types. They are used in China and foreign countries. Now, the horizontal fans are widely used in China.

2 In terms of the tunnels using large axial fans for ventilation in China in early days, such as Shenzhen Wutong Mountain Tunnel and Shanghai Yan' an Road Tunnel, the axial fans withadjustable rotary blade are adopted, but they are hardly used in actual operation. The selection of large axial fan shall meet the requirements of different operating periods.

3 After the completion of the civil works of ventilation system and before the installation of axial fan, the configuration parameters of axial fan shall be verified and it is an indispensable part of ventilation design.

11.3.2 The power calculation of axial fan shall meet the following requirements:

1 The total-pressure output power of axial fan shall be calculated by formula (11.3.2-1):

$$S_{th} = \frac{Q_a \cdot P_{tot}}{1000} \times \left(\frac{273 + t_0}{273 + t1}\right) \times \frac{P1}{P0} \qquad (11.3.2\text{-}1)$$

Where:

S_{th}—total-pressure output power of axial fan, i.e., idea power (kW);

Q_a—air volume flow of axial fan (m^3/s);

P_{tot}—design total pressure of axial fan (N/m^2);

t_1—ambient temperature of fan (℃);

t_0—normal temperature (℃), 20℃;

P_1—atmospheric pressure in fan environment (N/m^2);

P_0—normal atmospheric pressure (N/m^2);

2 The total-pressure input power of axial fan shall be calculated by formula (11.3.2-2):

$$S_{kw} = \frac{S_{th}}{\eta_f} \qquad (11.3.2\text{-}2)$$

Where:

S_{kw}—total-pressure input power of axial fan, i.e., shaft power (kW);

η_f—total-pressure efficiency of fan, 80%.

3 The motor input power required by axial fan shall be calculated by formula (11.3.2-3):

$$M_1 = \frac{S_{kw}}{\eta_m} \times k_1 \qquad (11.3.2\text{-}3)$$

Where:

M_1—motor input power (kW);

η_m—motor efficiency (%), 90% ~95%;

k_1—motor capacity safety factor, 1.05 ~1.10.

Background:

The shaft power of axial fan cannot be all converted into effective power to reflect the ventilation fan energy loss with efficiency.

11.3.3 The arrangement of axial fan shall meet the following requirements:

1 The horizontal axial fan should be selected; in the event of limited installation condition and insufficient installation space, the vertical axial fan may be selected.

2 Two or three axial fans should be installed in parallel; when 4 ones are operated in parallel, necessary technical demonstration shall be carried out in advance according to the specifications and performance parameters of fans. The model and performance parameters of each fan operating in parallel shall be exactly the same.

3 The anti-surge system should be provided for each axial fan in parallel.

4 The same air supply system or exhaust system may be equipped with 1 standby axial fan of the same model.

11.3.4 The air volume flow of axial fan should be adjusted by the combination of rotational speed control method and the fan quantity control method, and the power consumption of fan shall be fully considered. The air volume flow grade of tunnel ventilation shall be determined according to the change of traffic volume with time, and should be classified by grade.

Background:

The air volumeflow adjustment method of axial fan includes the rotational speed control method, fan quantity control method and the combination of such two methods.

11.3.5 According to the requirements of environmental protection and conditions, the active silencer should be placed on both ends or one end of axial fan to silence it; and the noise of axial fan may be calculated according to formula (11.3.5):

$$L_a = L_{sa} + 10 \cdot \lg(Q_a \cdot P_{tot}^2) \tag{11.3.5}$$

Where:

L_a—noise level [dB (A)];

L_{sa}—contrastive noise level [dB (A)].

11.3.6 The vibration velocity of axial fan should not exceed 6mm/s.

11.3.7 The motor of axial fan shall be a fully enclosed air-cooled squirrel-cage three-phase asynchronous motor and the ingress of protection of motor shall not be lower than IP55. The motor manufacturing shall meet the following requirements:

1 The output power of fan motor shall not be less than the required input power of fan.

2 When the requirements of ventilation system are met, the input power of installed fan's motor shall not be greater than the input power of the fan motor determined in ventilation design.

3 The voltage class of the motor of axial fan shall be selected according to power supply voltage, installation space, and control device; and the fan motor should be started by the means of voltage-reduced starting.

Background:
The voltage class of the axial fan motor used in highway tunnel ventilation includes 380V, 3,000V, 6,000V and 10kV, and the economical one shall be selected according to the applicable condition of each voltage class.

12 Design Principles of Ventilation Control

12.1 General

12.1.1 The mechanically ventilated tunnel fan shall have the function of manual control. The expressway and the Class-I highway tunnel should mainly adopt automatic control, and Class-Ⅱ, Class-Ⅲ and Class-Ⅳ highway tunnels may adopt automatic control mode.

***Background*:**

The purpose of ventilation control is, based on the premise of highway tunnel traffic safety, to control the ventilation equipment by monitoring the environmental parameters such as the concentration of harmful substances, air velocity and wind direction in tunnel. Meanwhile, ventilation control is an important measure to achieve energy-conservation operation of tunnel ventilation system by controlling the running time and quantity of ventilation equipment.

12.1.2 The control plan for ventilation system of highway tunnel shall be formulated in terms of normal working condition, abnormal working conditions such as fire and traffic congestion and ventilation requirements such as working conditions of maintenance and repair according to the ventilation mode.

***Background*:**

In design stage, ventilation system designer shall propose the control plan and strategy of ventilation system according to the number of fans and operation mode required for different working conditions, including the number of fans in each working condition, the combination mode of fans, and the forward or reverse rotation of fan; and smoke extraction and rescue program in fire, so that the monitoring system designers can set up corresponding facilities and write control software according to operation requirements of ventilation system to meet the ventilation standard of polluted air in tunnel and realize economical operation.

12.1.3 The linkage control among the ventilation control system, lighting control system, fire alarm and firefighting system, traffic monitoring system and central control system shall be realized.

Background:
The ventilation control system shall be used in combination with lighting control system, fire alarm and firefighting system, traffic monitoring system and central control system, in order to form an effective, reliable and timely control system to meet fan start-stop requirements in different conditions, especially in emergency condition and fire.

12.1.4 The fan control shall be set at a grade of air volume flow required by tunnel operation. The air volume flow should not be graded excessively detailed, and the operating power consumption and fan running time shall be fully considered. When there are axial flow air supply fan, axial flow exhaust fan and jet fan in tunnel ventilation system, a reasonable combined air volume flow grade shall be determined for each type of fan.

Background:
In general, the blade rotation speed of fan (including exhaust fan, air supply fan and jet fan) can continuously change its outputair volume flow, but if it adopts continuous control or excessively graded, for tunnels, on the one hand, the air volume flow sense is slow and so is the control efficiency; on the other hand, the control system is complicated, equipment consumption is large and the cost is increased. Therefore, the division of air volume flow grade should not be too detailed.

12.1.5 The fan control shall meet the following requirements:

1 When the daily traffic volume distribution is relatively constant or the diesel vehicle mixing rate changes little, the process control method should be adopted.

2 The start and stop of motor should not be too frequent.

3 Each unit (set) of fan shall be started at intervals, and the interval time shall be greater than 30s.

12.2 Smoke prevention and extraction control in case of tunnel fire

12.2.1 Smoke prevention and extraction control in fire shall work in cooperation with other monitoring systems such as tunnel fire alarm, closed-circuit television monitoring and traffic monitoring.

Background:

The tunnel control in emergency is a complex system. Ventilation and smoke extraction control in fire is not only an issue of how to start the fan to effectively exhaust smoke, but also shall work in cooperation with other monitoring systems such as tunnel fire alarm, closed-circuit television monitoring and traffic monitoring to form a comprehensive and reliable system solution.

12.2.2 The smoke prevention and extraction monitoring system shall meet the following requirements:

1 It shall have the functions of air velocity, air direction and fire monitoring.

2 It shall have the control and operation modes such as smoke prevention and extraction, escape guide and rescue command with different smoke extraction methods in different stages like safe evacuation and firefighting and rescue.

3 The smoke exhaust volume and air velocity control mode of corresponding system shall be reasonably determined according to the origin of fire.

4 It shall be able to adjust the smoke prevention and extraction system appropriately according to the actual situation and requirements of the fire scene.

12.2.3 The smoke prevention and extraction system shall be equipped with automatic control and manual control devices, and shall have the functions of field control, remote control and linkage control. The control commands given by the field control device shall be superior to other control commands in fire.

Background:

12.2.2 ~ 12.2.3 In the case of fire, the most critical issue of tunnel smoke control is that the smoke prevention and extraction facilities in tunnel can be started timely and accurately. In terms of control device, field control is more feasible than remote control to achieve this. Field personnel more directly knows more details of the actual field condition such as fire condition and traffic condition than remote monitoring; and the determined ventilation control requirements are more practical, therefore the field control is required to be superior to remote control.

12.2.4 The manual control device shall be installed in a safe place easy to operate, and shall have obvious signs and protection measures; and its operating button should be not more than 1.5m from the ground.

Background:

To ensure that the manual control device in the tunnel can be safely, timely and accurately activated, the manual control device shall be installed in a safe place easy to operate, and protective measures against fire and smoke shall be taken.

12.2.5 The motor starter, driving device, breaking device and control device of smoke exhaust fan shall be separated from fan airflow.

Background:

In the case of fire, the smoke temperature is high. In order to protect fan drive and control device from the damage caused by high temperature smoke, asa result of which the fan cannot work normally and the ventilation and firefighting and rescue are affected, necessary measures are required to be taken to prevent smoke from electric, drive and monitoring device of smoke exhaust fan.

12.2.6 When a fire occurs in one tube of the two-tube uni-directional tunnel and ventilation and smoke extraction and rescue are required, traffic control shall be carried out to both tubes of the tunnel and the corresponding ventilation and smoke extraction system shall be activated.

Appendix A
On-way Resistance Coefficient

A.0.1 The on-way resistance coefficient of straight duct may be calculated by formula (A.0.1):

$$\lambda = \frac{1}{\left(1.1138 - 2\lg\frac{\Delta}{D}\right)^2} \tag{A.0.1}$$

Where:

Δ—average wall roughness (mm), subject to Table A.0.1;

D—hydraulic diameter of duct section (m).

Table A.0.1 Average wall roughness

Wall surface material and characteristics		Δ(mm)
Concrete wall surface	Good flatness	0.3 ~ 0.8
	Average flatness	2.5
	Roughness	3 ~ 9
Cement mortar wall surface	Good flatness	0.3 ~ 0.8
	Average flatness	1.0 ~ 2.0
	Roughness	2.9 ~ 6.4
Ceramic tiling		1.4

A.0.2 The on-way resistance coefficient of curve zone with a horizontal curve radius $R < 2000$m may be calculated by formula (A.0.2):

$$\lambda_c = 1.8235\lambda \cdot R^{-0.078} \tag{A.0.2}$$

Where:

λ_e—resistance loss coefficient of curve tunnel wall;

λ—resistance loss coefficient of tunnel wall;

R—horizontal curve radius of curve zone (m).

Appendix B
Pressure Loss Coefficient of U-shaped and Z-shaped Ducts

B.0.1 The pressure loss coefficient of curve duct bending without guide blade may be subject to the following requirements:

1 The pressure loss coefficient ζ_b of 90° circular curve duct bending without guide blade may refer to Table B.0.1-1. When the curve duct is not 90°, it shall multiply the correction factor ε_θ for correction and the correction factor may refer to Table B.0.1-2. The curvature radius R of curve pipe should be within the range of (1 ~ 4)D.

Table B.0.1-1 Pressure loss coefficient ζ_b of 90° circular duct bending

R/D	0.5	0.75	1.0	1.5	2.0	2.5
ζ_b	0.71	0.5	0.25	0.15	0.13	0.12

Note: D refers to thehydraulic diameter of exhaust duct (m).

Table B.0.1-2 Pressure loss correction factor ε_θ of circular duct bending

θ(°)	0	20	30	45	60	75	90	110	130	150	180
ε_θ	0	0.31	0.45	0.6	0.78	0.9	1.0	1.13	1.2	1.28	1.4

2 When the Reynolds number (Re) $\geqslant 20 \times 10^4$, the pressure loss coefficient ζ_b of the 90° rectangular duct without guide blade (Figure B.0.1-2) may refer to Table B.0.1-3; and when Re $< 20 \times 10^4$, it may be calculated by formula (B.0.1-1):

$$\zeta_b' = \varepsilon_{Re} \times \zeta_b \quad \text{(B.0.1-1)}$$

Where:

ε_{Re}—correction factor, subject to Table B.0.1-4.

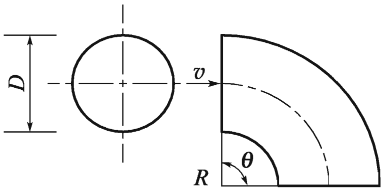


Figure B. 0. 1-1 Sketch of 90° circular duct bending

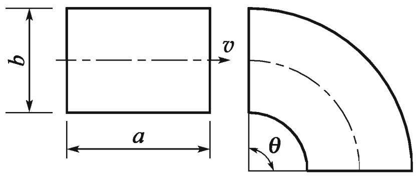


Figure B. 0. 1-2 Sketch of 90° rectangular duct bending

Table B. 0. 1-3 Pressure loss coefficient ζ_b of 90° rectangular duct bending

R/b	a/b										
	0.25	0.5	0.75	1.0	1.5	2.0	3.0	4.0	5.0	6.0	8.0
0.5	1.5	1.4	1.3	1.2	1.1	1.0	1.0	1.1	1.1	1.2	1.2
0.75	0.57	0.52	0.48	0.44	0.40	0.39	0.39	0.40	0.42	0.43	0.44
1.0	0.27	0.25	0.23	0.21	0.19	0.18	0.18	0.19	0.20	0.27	0.21
1.5	0.22	0.20	0.19	0.17	0.15	0.14	0.14	0.15	0.16	0.17	0.17
2.0	0.20	0.18	0.16	0.15	0.14	0.13	0.13	0.14	0.14	0.15	0.15

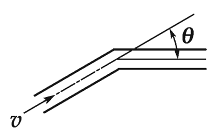
Table B. 0. 1-4 Pressure loss correction factor ε_{Re} of 90° rectangular duct bending

R/b	$Re \times 10^4$								
	1	2	3	4	6	8	10	14	≥20
0.5	1.40	1.26	1.19	1.4	1.09	1.06	1.04	1.0	1.0
≥0.75	2.0	1.77	1.64	1.56	1.46	1.38	1.30	1.15	1.0

3 The pressure loss coefficient ζ_b of circular Z-shaped duct may be calculated by formula (B. 0. 1-2) or subject to Table B. 0. 1-5.

$$\zeta_b = 0.946\sin^2\left(\frac{\theta}{2}\right) + 2.05\sin^4\left(\frac{\theta}{2}\right) \tag{B. 0. 1-2}$$

Table B. 0. 1-5 Pressure loss coefficient ζ_b of circular Z-shaped duct

θ	ζ_b	Diagram
15°	0.022	
30°	0.073	
45°	0.183	
60°	0.365	
90°	0.99	
120°	1.86	

4 The pressure loss coefficient ζ_b of rectangular Z-shaped duct may refer to Figure B.0.1-3.

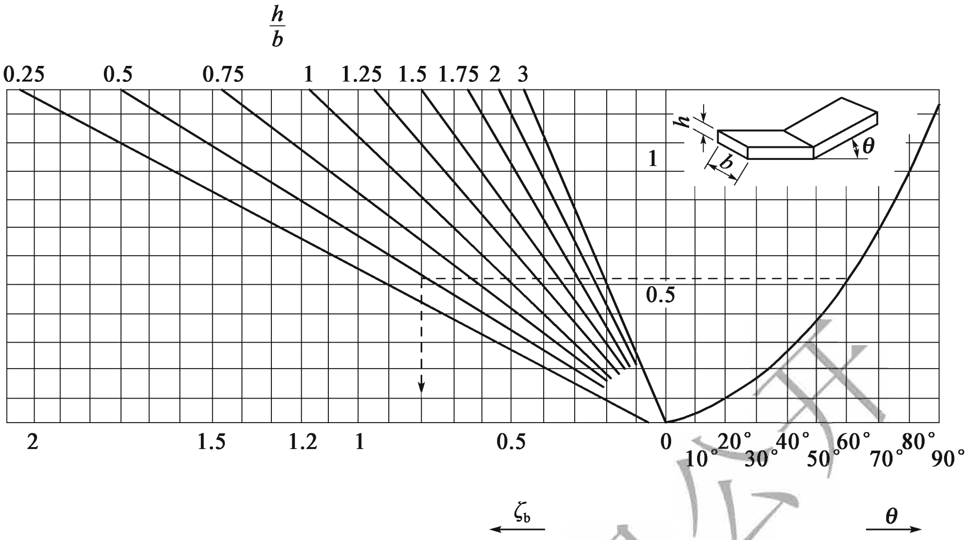


Figure B.0.1-3 Pressure loss coefficient ζ_b of rectangular Z-shaped duct

5 The pressure loss coefficient ζ_b of variable section of circular or rectangular Z-shaped duct may refer to Figure B.0.1-4.

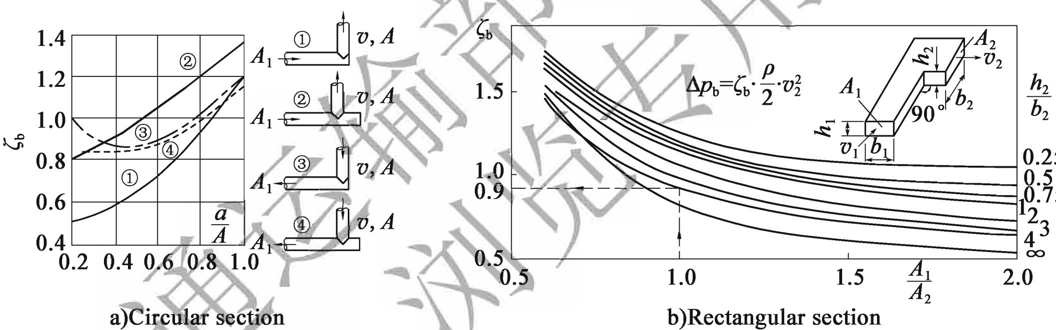


Figure B.0.1-4 Pressure loss coefficient ζ_b of Z-shaped duct of variable section

A_1, A_2-sectional area

B.0.2 The pressure loss coefficient of curve duct with guide blade may refer to the following provisions:

1 In the curve zone of circular or rectangular duct with large pressure loss, the guide blades shall be installed in the following two cases to minimize the pressure loss ofduct:

1) When $R < 1.6D$, the guide blades shall be installed;

2) When the air passes through the U-shaped and Z-shaped duct zone, the guide blades shall be installed at the position where theflow deflection and vortex flow are not

expected in the vicinity of the intake of air supply fan and the front end of duct.

2 When guide blades are installed in curve pipe, the relationship between the bending angleθ and the ζ_b in the sharply curve part of the rectangular section shall meet the following requirements:

1) Whenθ is small, the ζ_b is almost in direct proportion to θ.

2) Whenθ is within 60° ~ 90°, the ζ_b basically doesn't change with the change of θ.

3) The determination of relative value of bending angle may refer to Figure B.0.2-1.

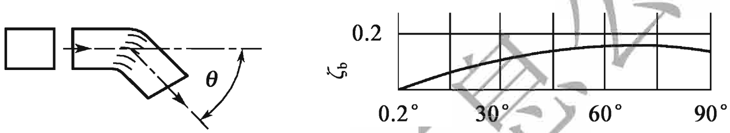


Figure B.0.2-1 Relational graph of angleθ and ζ_b of U-shaped duct with guide blade

3 The design dimension of the guide blade shall be determined by formula (B.0.2-1) ~ (B.0.2-3) in combination with Figure B.0.2-2; the structure of guide blade shall ensure that the inspectors can pass through it. The guide blade may be made into two shapes, one is the wing shape that is simplified into the curve cylindrical surface, and the other is the thin circle in the shape of concentric arc, as shown in Figure B.0.2-3. The section size of wing-shaped guide blade mayrefer to Table B.0.2-1.

$$W/d = 4 \sim 6 \tag{B.0.2-1}$$

$$R/d = 1.5 \sim 2.6 \tag{B.0.2-2}$$

$$L/d = 2.0 \sim 3.0 \tag{B.0.2-3}$$

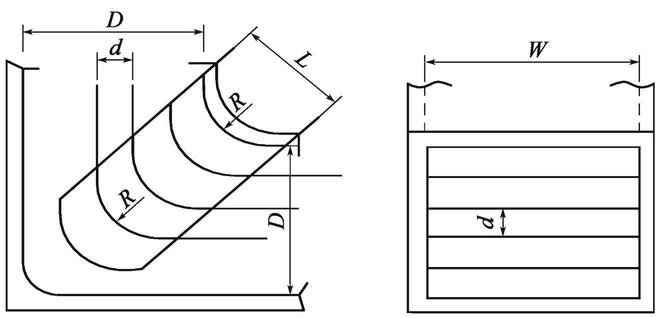
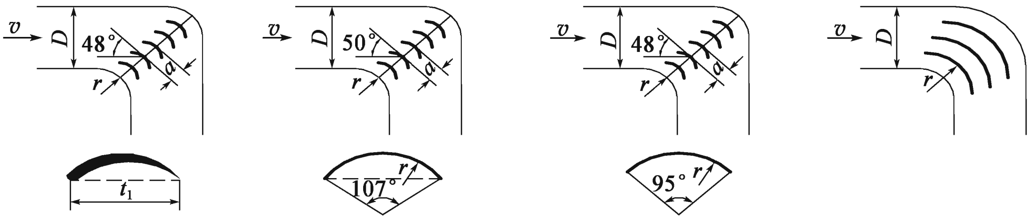


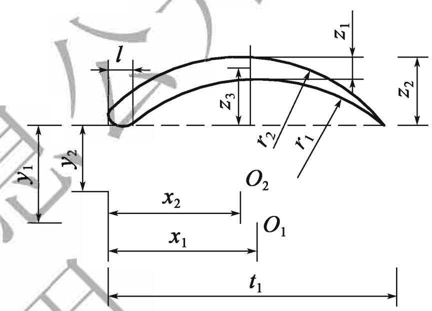
Figure B.0.2-2 Design chart of guide blade size



a)Wing shape　b)107°thin circle　c)95°thin circle　d)Concentric circle

Figure B. 0. 2-3　Guide blade in U-shaped duct

Table B. 0. 2-1　Section size of wing-shaped guide blade

Symbol	Relative size	Symbol	Relative size	Diagram	
x_2	$0.519t_1$	y_2	$0.215t_1$	Diagram	
x_2	$0.489t_1$	z_1	$0.139t_1$		
r_1	$0.663t_1$	z_2	$0.338t_1$		
r_2	$0.553t_1$	z_3	$0.268t_1$		
y_1	$0.463t_1$	l	$0.033t_1$		

Note: the chord length t_1 may be that of 90° arc, i. e. , $t_1 = \sqrt{2}r$.

1) The normal number of guide blades n may be calculated by formula (B. 0. 2-4):

$$n = 2.13 \times \left(\frac{r}{D}\right)^{-1} - 1 \quad \text{(B. 0. 2-4)}$$

2) The minimum number $n_{\min}$ of guide blades may be calculated by formula (B. 0. 2-5):

$$n_{\min} = 0.9 \times \left(\frac{r}{D}\right)^{-1} \quad \text{(B. 0. 2-5)}$$

3) The reduced number n′ of guide blades may be calculated by formula (B. 0. 2-6):

$$n' = 1.4 \times \left(\frac{r}{D}\right)^{-1} \quad \text{(B. 0. 2-6)}$$

4) If the number of blades is to be reduced, it may start from the blade close to the outer wall of curve pipe in order.

4　The loss coefficient of U-shaped duct with guide blade mayrefer to Table B. 0. 2-2 ~ Table B. 0. 2-4; if necessary the loss coefficient may be determined by model test.

Table B.0.2-2 Pressure loss coefficient ζ_b of rectangular U-shaped duct with wing-shaped guide blade ($\theta = 90°$)

Number of blades	r/D						
	0	0.1	0.2	0.3	0.4	0.5	0.6
Normal number of blades	0.35	0.25	0.19	0.19	0.20	0.25	0.35
Reduced number of blades	0.35	0.25	0.17	0.14	0.16	0.22	0.34
Minimum number of blades	0.47	0.35	0.29	0.26	0.20	0.18	0.21

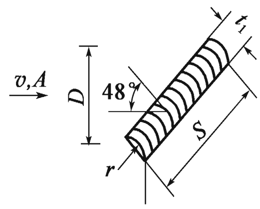
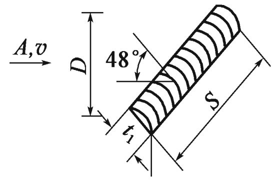
Note: when $Re < 10^5$, the data in the table shall multiply the correction factor k_{Re}, which may refer to Table B.0.2-5.

Table B.0.2-3 Pressure loss coefficient ζ_b of rectangular U-shaped duct with thin circular guide blade ($\theta = 90°$)

Number of blades	r/D						
	0	0.05	0.10	0.15	0.20	0.25	0.30
Normal number of blades	0.44	0.37	0.32	0.28	0.25	0.25	0.23
Reduced number of blades	0.44	0.37	0.32	0.26	0.22	0.21	0.17
Minimum number of blades	0.59	0.50	0.45	0.41	0.37	0.34	0.31

Note: when $Re < 10^5$, the data in the table shall multiply the correction factor k_{Re}, which may refer to Table B.0.2-5.

Table B.0.2-4 Pressure loss coefficient ζ_b of circular U-shaped duct with wing-shaped guide blade ($\theta = 90°$)

Characteristics of U-shaped duct	Loss coefficient ζ_b	Diagram
Smooth turn, normal number of blades $a = 3D/t_1 - 1$	$\zeta_b = 0.23k_{Re} + 1.28\lambda$	
Smooth turn, reduced number of blades $a = 2D/t_1$	$\zeta_b = 0.15k_{Re} + 1.28\lambda$	
Chamfered edge of turn, normal number of blades $a = 3D/t_1 - 1$	$\zeta_b = 0.30k_{Re} + 1.28\lambda$	
Chamfered edge of turn, reduced number of blades $a = 2D/t_1$	$\zeta_b = 0.23k_{Re} + 1.28\lambda$	
Chamfered edge of turn, reduced number of blades (the first and the second blades are removed from the outer wall)	$\zeta_b = 0.21k_{Re} + 1.28\lambda$	

Note: in the formula of loss coefficient, k_{Re} is a parameter in relation to Re, which may refer to Table B.0.2-5.

Table B.0.2-5 Correction factor k_{Re}

$Re \times 10^{-5}$	0.3	0.4	0.5	0.6	0.8	1.0	1.4	2.0	3.0	>6.0
k_{Re}	2.10	1.80	1.60	1.50	1.35	1.23	1.12	1.0	0.9	0.8

5 As a special section form, when guide blade is installed in the tunnel ceiling duct (semicircular cone), the pressure loss coefficient may be determined by Figure B.0.2-4.

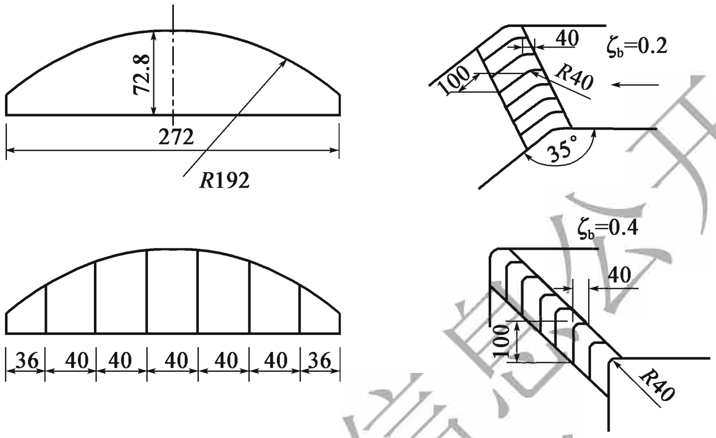


Figure B.0.2-4 Loss coefficient of ceiling duct bending (unit: cm)

Appendix C
Other Pressure Loss Coefficient of Tunnels and Ducts

C. 0. 1 The pressure loss coefficient of contracting and expanding ducts may refer to the following provisions:

1 When the pressure loss coefficient of suddenly expanding andcontracting duct is defined by the relatively larger air velocity and may refer to Figure C. 0. 1-1.

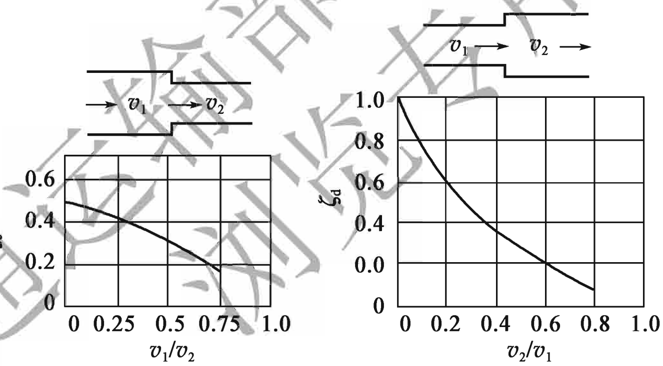


Figure C. 0. 1-1 Pressure loss coefficient of suddenly variable section

2 The diagrams of gradually expanding andcontracting ducts refer to Figure C. 0. 1-2 and Figure C. 0. 1-3 and the pressure loss coefficient may refer to Table C. 0. 1-1 and Table C. 0. 1-2.

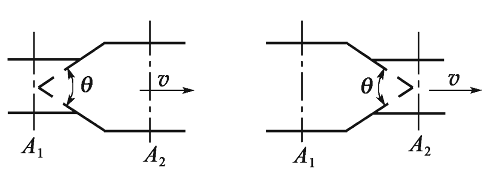


Figure C. 0. 1-2 Diagram ofgradually variable circular duct

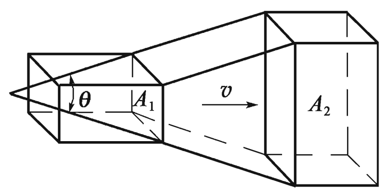


Figure C. 0. 1 -3 Diagram ofgradually expanding rectangular duct

Table C. 0. 1-1 Pressure loss coefficient ofgradually variable circular duct

Type	ζ										
Gradually expanding	$\xi = k \cdot \left(\frac{A_2}{A_1} - 1\right)^2$	θ	8°	10°	12°	15°	20°	25°			
		k	0. 14	0. 16	0. 22	0. 30	0. 42	0. 62			
Gradually contracting	$\zeta = k_1 \cdot k_2$	θ	10°	20°	40°	60°	80°	100°			
		k_1	0. 40	0. 25	0. 20	0. 20	0. 30	0. 40			
		A_2/A_1	0. 1	0. 2	0. 3	0. 4	0. 5	0. 6	0. 7	0. 8	0. 9	1. 0
		k_2	0. 40	0. 38	0. 36	0. 34	0. 30	0. 27	0. 20	0. 16	0. 10	0

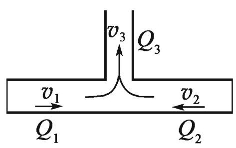
Table C. 0. 1-2 Pressure loss coefficient ofgradually expanding rectangular duct

A_2/A_1	θ				
	10°	15°	20°	25°	30°
1. 25	0. 02	0. 03	0. 05	0. 06	0. 07
1. 50	0. 03	0. 06	0. 10	0. 12	0. 13
1. 75	0. 05	0. 09	0. 14	0. 17	0. 19
2. 00	0. 06	0. 13	0. 20	0. 23	0. 26
2. 25	0. 08	0. 16	0. 26	0. 30	0. 33
2. 50	0. 09	0. 19	0. 30	0. 36	0. 39

C. 0. 2 The pressure loss coefficient of diverging and merging zones may refer to the following provisions:

1 If it is a merging type, the pressure loss coefficient ζ_{1-3}, ζ_{2-3} may refer to Table C. 0. 2-1.

Table C. 0. 2-1 Pressure loss coefficient ofmerging duct

Q_1/Q_3	Q_2/Q_3	ζ_{1-3}	ζ_{2-3}	Diagram
1. 00	0	0. 91	0. 55	
0. 95	0. 05	0. 84	0. 50	
0. 90	0. 10	0. 78	0. 46	
0. 85	0. 15	0. 71	0. 42	
0. 80	0. 20	0. 64	0. 38	
0. 75	0. 25	0. 58	0. 35	
0. 70	0. 30	0. 52	0. 33	
0. 65	0. 35	0. 46	0. 31	
0. 60	0. 40	0. 40	0. 29	
0. 55	0. 45	0. 34	0. 29	
0. 50	0. 50	0. 31	0. 31	

2 If it is a diverging type, the pressure loss coefficient ζ_{1-2}, ζ_{1-3} may refer to Table C.0.2-2.

Table C.0.2-2 Pressure loss coefficient of diverging duct

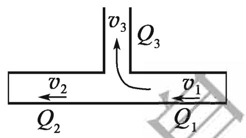
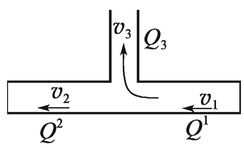
A_2/A_1	Diverging pressure loss coefficient ζ_{1-2} of main stream									
	Q_2/Q_1									
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
0.5	0.72	0.48	0.28	0.13	0.05	0.04	0.09	0.18	0.31	0.50
1.0	0.05	0.05	0.05	0.05	0.06	0.13	0.22	0.30	0.38	0.48
Diagram										

Table C.0.2-2 (Cont'd)

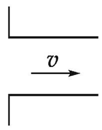
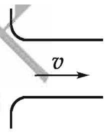
A_3/A_1	Diverging pressure loss coefficient ζ_{1-3} of branch stream									
	Q_3/Q_1									
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
0.25	0.55	0.50	0.60	0.85	1.20	1.80	3.10	4.35	6.00	9.00
1.0	0.67	0.55	0.46	0.37	0.32	0.29	0.29	0.30	0.37	0.48
Diagram										

C.0.3 The local resistance coefficient of entrance, exit and other parts may refer to the following provisions:

1 The calculation of local pressure loss of the entrance, exit and other parts shall be based on the average flow velocity v in pipe.

2 Thelocal resistance coefficient of entrance may refer to Table C. 0. 3-1.

Table C. 0. 3-1 Loss coefficient of entrance

Shape	ζ_e	Diagram
Right angle with sharp edge	0. 50 ~ 0. 60	
Rounded edge, chamfer	0. 03 ~ 0. 05	

3 Thelocal resistance coefficient of exit shall be determined according to different forms:

1) Straight exit (Figure C. 0. 3-1): ζ_{ex} = 1. 0;

2) 90° elbow exit (Figure C. 0. 3-1), ζ_{ex} may refer to Table C. 0. 3-2 and Table C. 0. 3-3;

3) Thelocal resistance coefficient of diffused exit may refer to Figure C. 0. 3-2.

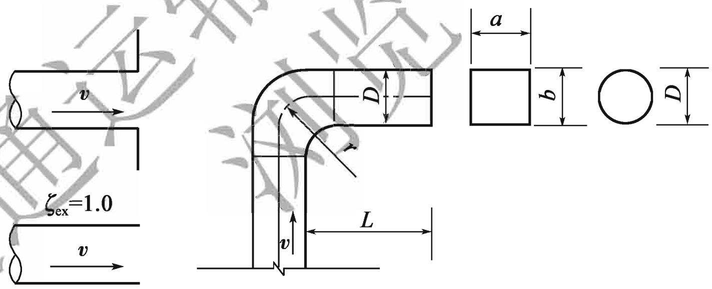


Figure C. 0. 3-1 Diagram of straight and 90° elbow exit

Table C. 0. 3-2 Local resistance coefficient ζ_{ex} of 90° elbow exit of the rectangular duct

r/b	L/b									
	0	0. 5	1. 0	1. 5	2. 0	3. 0	4. 0	6. 0	8. 0	12. 0
0. 50	3. 0	3. 1	3. 2	3. 0	2. 7	2. 4	2. 2	2. 1	2. 1	2. 0
0. 75	2. 2	2. 2	2. 1	1. 8	1. 7	1. 6	1. 6	1. 5	1. 5	1. 5
1. 00	1. 8	1. 5	1. 4	1. 4	1. 3	1. 3	1. 2	1. 2	1. 2	1. 2
1. 50	1. 5	1. 2	1. 1	1. 1	1. 1	1. 1	1. 1	1. 1	1. 1	1. 1
2. 50	1. 2	1. 1	1. 1	1. 0	1. 0	1. 0	1. 0	1. 0	1. 0	1. 0

Table C. 0. 3-3 Local resistance coefficient ζ_{ex} of 90° elbow exit of the circular duct

r/D	0	0.28	0.5	1.0
ζ_e	3.0	1.9	1.6	1.4

4 The pressure loss coefficient of the rectangular or circular duct with grille (Figure C. 0. 3-3) mayrefer to Table C. 0. 3-4 and the n in table may be calculated by formula (C. 0. 3-1).

$$n = A_0'/A_0 \qquad (C.0.3\text{-}1)$$

Where:

n—wind area ratio of grille;

A_0'—active area of grille (mm^2);

A_0—sectional area of duct (mm^2).

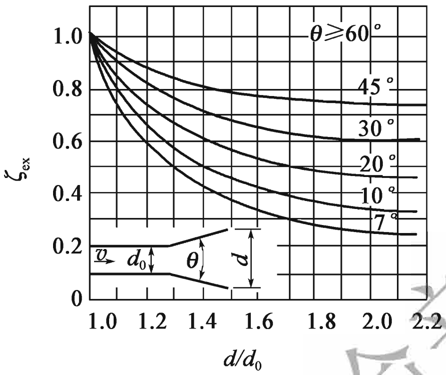


Figure C. 0. 3-2 Local resistance coefficient of diffused exit

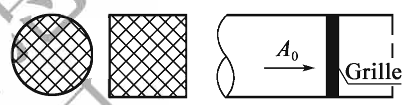


Figure C. 0. 3-3 Diagram of grille in duct

Table C. 0. 3-4 Pressure loss coefficient ζ_0 of duct with grille

n	0.30	0.40	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.90	1.0
ζ_0	6.20	3.00	1.70	1.30	0.97	0.75	0.58	0.44	0.32	0.14	0

5 When the duct exit, entrance and variable section are grilled, thelocal resistance coefficient ζ_b shall be corrected by formula (C. 0. 3-2).

$$\zeta_b = \zeta_b' + \zeta_0 \qquad (C.0.3\text{-}2)$$

Where:

ζ_b—local complex loss coefficient of duct when grille is installed;

ζ_b'—local loss coefficient of duct without grille;

ζ_0—local resistance coefficient of grille, subject to Table C. 0. 3-4.

Appendix D
Common Units and Unit Conversion in Fluid Mechanics

D.0.1 Common units

Unit category	Measurement	Name	Symbol	
			Chinese	Letter(s)
Basic units	Length	Meter	米	m
	Time	Second	秒	s
	Mass	Kilogram	千克	kg
Derived units	Force	Newton	牛	N
	Density	Kilogram per cubic meter	千克/米^3	kg/m^3
	Gravity density	Newton per cubic meter	牛/米^3	N/m^3

D.0.2 Unit conversion

1 Conversion of force units

Unit	Newton (N)	Kilogram force (kgf)	Pound-force (Ibf)	Dyne (dyn)
Newton (N)	1	0.102	0.225	10^5
Kilogram force (kgf)	9.807	1	2.21	9.8×10^5
Pound-force (Ibf)	4.45	0.454	1	4.45×10^5
Dyne (dyn)	10^{-5}	1.02×10^{-6}	2.25×10^{-6}	1

2 Conversion of mass units

Unit	Ton (t)	Kilogram (kg)	Long ton (UKton)	Pound (lb)
Ton (t)	1	1,000	0.9842	2,205
Kilogram (kg)	0.001	1	9.842×10^{-4}	2.205
Long ton (UKton)	1.0161	1,016.1	1	2,240.5
Pound (lb)	4.535×10^{-4}	0.454	4.463×10^{-4}	1

3 Conversion of power units

Unit	Watt (W)	Kilogram force · meter/second (kgf · m/s)	Calorie/second (cal/s)	Horsepower (PS)
Watt (W)	1	9.807	0.2388	1.36×10^{-3}
Kilogram force · meter/second (kgf · m/s)	0.10197	1	0.0243	1.39×10^{-4}
Calorie/second (cal/s)	4.187	41.058	1	5.69×10^{-3}
Horsepower (PS)	735.5	7,212.8	175.64	1

4 Conversion of pressure units

Unit	Newton/square meter (N/m^2) (Pa)	Bar (bar)	Technical atmosphere (at)	Normal atmospheric pressure (atm)	Millimeter of mercury (mmHg)	Millimeter of water (mmH_2O)
Newton/square meter (N/m^2) (Pa)	1	10^{-5}	1.02×10^{-5}	9.87×10^{-6}	7.5×10^{-3}	0.102
Bar (bar)	10^5	1	1.02	0.987	75	10,200
Technical atmosphere (at)	98,067	0.98	1	0.9678	735.6	10^4
Normal atmospheric pressure (atm)	101,325	1.01325	1.033	1	760	10,332
Millimeter of mercury (mmHg)	133.32	133.32×10^{-5}	1.36×10^{-3}	1.32×10^{-3}	1	13.6
Millimeter of water (mmH_2O)	9.807	9.807×10^{-5}	10^{-4}	9.679×10^{-5}	7.356×10^{-2}	1

Appendix E
Examples of Ventilation Calculation

Example E-1 Longitudinal ventilation with full jet stream

(1) Uni-directional tunnel

① Calculation conditions

Tunnel length	$L = 1,537\text{m}$
Sectional area of tunnel	$A_r = 63.85\text{m}^2$
Hydraulic diameter of cross section	$D_r = 8.166\text{m}$
Design PHV of hybrid vehicles	$N = 1,984\text{veh./h}$
Ratio of large vehicles	$r_1 = 59\%$
Design speed	$\upsilon_t = 60\text{km/h} = 16.67\text{m/s}$
Natural air velocity in tunnel	$\upsilon_n = 2.5\text{m/s}$
Design air volume flow	$Q_r = 450\text{m}^3/\text{s}$
Ventilation air velocity	$\upsilon_r = 450/63.85 = 7.05\text{m/s}$

② Pressure rise demand in tunnel

$$\Delta p = \Delta p_r + \Delta p_m - \Delta p_t$$

By formula (7.4.1-1) ~ formula (7.4.1-3), then:

$$\Delta p_r = \left(1 + \zeta_e + \lambda_r \cdot \frac{L}{D_r}\right) \cdot \frac{\rho}{2} \cdot v_r^2$$

$$= \left(1 + 0.6 + 0.025 \times \frac{1\,537}{8.17}\right) \times 0.6 \times 7.05^2$$

$$= 187.97\text{N/m}^2$$

By formula (7.2.2) and given $v_n = 2.5$m/s:

$$\Delta p_m = \left(1 + \zeta_e + \lambda_r \cdot \frac{L}{D_r}\right) \cdot \frac{\rho}{2} \cdot v_n^2$$

$$= \left(1 + 0.6 + 0.025 \times \frac{1\,537}{8.17}\right) \times 0.6 \times 2.5^2$$

$$= 23.64\text{N/m}^2$$

By formula (7.3.2), then:

$$\Delta p_t = \frac{A_m}{A_r} \cdot \frac{\rho}{2} \cdot n_C \cdot (v_t - v_r)^2$$

$$= \frac{3.6}{63.85} \times 0.6 \times 50.82 \times (16.67 - 7.05)^2$$

$$= 159.04\text{N/m}^2$$

$$\Delta p = 187.97 + 23.64 - 159.04$$

$$= 52.57\text{N/m}^2$$

③ Quantity demand of 900-model jet fans

The pressure rise Δp_j of each 900-model jet fan is:

$$\Delta p_j = \rho \cdot v_j^2 \cdot \frac{A_j}{A_r} \cdot \left(1 - \frac{v_r}{v_j}\right) \cdot \eta$$

$$= 1.2 \times 25^2 \times \frac{0.636}{63.85} \times \left(1 - \frac{7.05}{25}\right) \times 0.85$$

$$= 4.56\text{N/m}^2$$

Therefore,

$$i = \frac{\Delta p}{\Delta p_j} = \frac{52.57}{4.56}$$

Thus, twelve 900-model jet fans are required, and to be arranged in six groups.

④ Quantity demand of 1120-model jet fans

The pressure rise Δp_j of each 1120-model jet fan is:

$$\Delta p_j = \rho \cdot v_j^2 \cdot \frac{A_j}{A_r} \cdot \left(1 - \frac{v_r}{v_j}\right) \cdot \eta$$

$$= 1.2 \times 30^2 \times \frac{0.98}{63.85} \times \left(1 - \frac{7.05}{30}\right) \times 0.85$$

$$= 10.78\text{N/m}^2$$

Therefore,

$$i = \frac{\Delta p}{\Delta p_j} = \frac{52.57}{10.78} = 4.9 \approx 5 \text{jet fans}$$

Thus, six 1120-model jet fans are required, and to be arranged in three groups.

(2) Bi-directional tunnel

① Calculation conditions

Apart from the relevant calculation conditions listed in item (1), the others are as follows:

Design PHV of hybrid vehicles	$N = 759$ veh./h
Directional distribution factor ofupline traffic volume	$D = 60\%$
Design speed	$v_t = 40\text{km/h} = 11.11\text{m/s}$
Natural air velocity in tunnel	$v_n = 1.5\text{m/s}$
Design air volume flow	$Q_r = 172\text{m}^3/\text{s}$
Ventilation air velocity	$v_r = 172/63.85 = 2.69\text{m/s}$

② Pressure rise demand in tunnel

Assuming that jet stream direction of the jet fan is consistent with that of the main traffic flow direction,

$$\begin{aligned}\Delta p_r &= \left(1 + \zeta_e + \lambda_r \cdot \frac{L}{D_r}\right) \cdot \frac{\rho}{2} \cdot v_r^2 \\ &= \left(1 + 0.6 + 0.025 \times \frac{1\,537}{8.17}\right) \times 0.6 \times 2.69^2 \\ &= 27.37\text{N/m}^2\end{aligned}$$

$$\begin{aligned}\Delta p_m &= \left(1 + \zeta_e + \lambda_r \cdot \frac{L}{D_r}\right) \cdot \frac{\rho}{2} \cdot v_n^2 \\ &= \left(1 + 0.6 + 0.025 \times \frac{1\,537}{8.17}\right) \times 0.6 \times 1.5^2 \\ &= 8.51\text{N/m}^2\end{aligned}$$

$$\Delta p_t = \frac{A_m}{A_r} \cdot \frac{\rho}{2} \cdot n_+ \cdot (v_t + v_r)^2 - \frac{A_m}{A_r} \cdot \frac{\rho}{2} \cdot n_- \cdot (v_t - v_r)^2$$

Quantity of the upline vehicles n_+ is:

$$n_+ = \frac{759 \times 60\% \times 1537}{3600 \times 11.11} = 17.5 \text{vehicles}$$

Quantity of the downline vehicles n_- is:

$$n_{-} = \frac{759 \times (1 - 60\%) \times 1537}{3600 \times 11.11} = 11.67 \text{vehicles}$$

Suppose $A_{m+} = A_{m-}$,

$$\Delta p_t = \frac{3.6}{63.85} \times \frac{1.2}{2}[17.5 \times (11.11 - 2.69)^2 - 11.67 \times (11.11 + 2.69)^2]$$
$$= -84.75 \text{N/m}^2$$

With the above results,

$$\Delta p = \Delta p_r + \Delta p_m - \Delta p_t = 27.37 + 8.51 - (-84.75) = 120.63 \text{N/m}^2$$

③ Quantity demand of jet fan

By the calculation method of uni-directional tunnel, for 900-model jet fan:

$$\Delta p_j = 5.67 \text{N/m}^2$$
$$i = \frac{\Delta p}{\Delta p_j} = \frac{120.63}{5.67} = 21.3 \approx 22 \text{台}$$

Twenty-two jet fans are required and to be arranged in eleven groups.

For 1120-model jet fan,

$$\Delta p_j = 12.83 \text{N/m}^2$$
$$i = \frac{\Delta p}{\Delta p_j} = \frac{120.63}{12.83} = 9.4 \approx 10 \text{台}$$

Ten jet fans are required and to be arranged in five groups.

Example E-2 Longitudinal ventilation with Saccardo nozzle

(1) Calculation conditions of tunnel

Traffic directionUni-directional traffic

Tunnel length	$L = 2,150\text{m}$
Sectional area of tunnel	$A_r = 63.85\text{m}^2$
Hydraulic diameter of cross section	$D_r = 8.17\text{m}$
Design PHV of hybrid vehicles	$N = 2,480\text{veh./h}$
Ratio of large vehicles	$r_1 = 0.3$ ($A_m = 2.3\text{m}^2$)
Ventilation air velocity	$v_t = 60\text{km/h} = 16.67\text{m/s}$
Design air volume flow	$Q_t = 490\text{m}^3/\text{s}$

Refer to figure E-1 for the centralized ventilation facility.

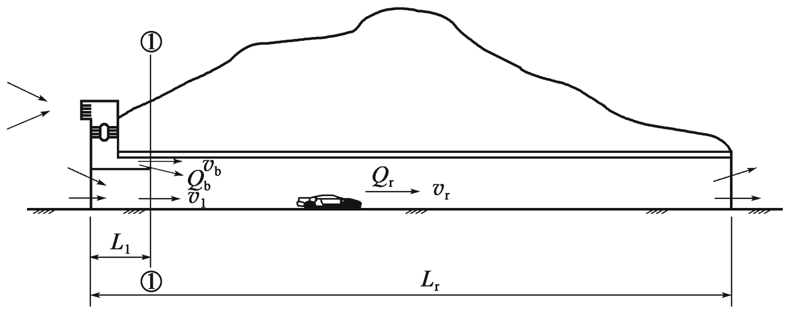


Figure E-1 Sketch of tunnel with the longitudinal ventilation with Saccardo nozzle

(2) Pressure rise demand in tunnel Δp

$$\Delta p = \left(\zeta_e + \lambda_r \cdot \frac{L_1}{D_1}\right) \cdot \frac{\rho}{2} \cdot v_1^2 + \left(1 + \lambda_r \cdot \frac{L - L_1}{D_r}\right) \cdot \frac{\rho}{2} \cdot v_r^2 - \Delta p_t + \Delta p_m$$

$$v_1 = \frac{Q_r - Q_b}{A_r - A_b}$$

For simplification, given $L_1 = 0$, assume $v_1 = 0.5v_r$, therefore:

$$\Delta p = \left(\frac{1}{4}\zeta_e + 1 + \lambda_r \cdot \frac{L}{D_r}\right) \cdot \frac{\rho}{2} \cdot v_r^2 - \Delta p_t + \Delta p_m$$

$$v_r = \frac{490}{63.85} = 7.67\text{m/s}$$

$$\frac{\rho}{2} \cdot v_r^2 = 0.6 \times 7.67^2 = 35.3\text{N/m}^2$$

$$\Delta p_r = \left(\frac{1}{4}\zeta_e + 1 + \lambda_r \cdot \frac{L}{D_r}\right) \cdot \frac{\rho}{2} \cdot v_r^2$$

$$= \left(\frac{1}{4} \times 0.6 + 1 + 0.025 \times \frac{2\,150}{8.17}\right) \times 35.3 = 272.83\text{N/m}^2$$

$$\Delta p_t = \frac{A_m}{A_r} \cdot n \cdot \frac{\rho}{2} \cdot (v_t - v_r)^2$$

Where: $A_m = 2.3\text{m}^2$; $n_C = \frac{2\,480 \times 2\,150}{3\,600 \times 16.67} = 88.85$。

$$\Delta p_t = \frac{2.3}{63.85} \times 88.85 \times 0.6 \times (16.67 - 7.67)^2$$

$$= 155.55\text{N/m}^2$$

$$\Delta p_m = \left(1 + \zeta_e + \lambda_r \cdot \frac{L}{D_r}\right) \cdot \frac{\rho}{2} \cdot v_n^2$$

Given $v_n = 2.8\text{m/s}$

$$\Delta p_m = \left(1 + 0.6 + 0.025 \times \frac{2\,150}{8.17}\right) \times 0.6 \times 2.8^2 = 38.47\text{N/m}^2$$

$$\Delta p = 272.83 - 155.55 + 38.47 = 155.75\text{N/m}^2$$

(3) Air volume flow of jet fan Q_b, air velocity at the air outlet υ_b and area of air outlet A_b

In this example, it is assumed that $A_b = 12\text{m}^2$ and it has a little influence on the cost of air outlet structure. Given the angle between jet stream direction of the air outlet and tunnel axis is set to 0°, let $\cos\beta = 1.0$ and $K_b = 0.9$.

① Calculation of air velocity υ_b (It is hypothesized that $A_b = 12\text{m}^2$)

The formula (7.6.3) is rewritten as:

$$\Delta p_b = 2\left(\frac{Q_b}{Q_r}\right)\left[\frac{K_b \cdot v_b \cdot \cos\beta}{v_r} - 2 + \left(\frac{Q_b}{Q_r}\right)\right]\cdot\frac{\rho}{2}\cdot v_r^2$$

In this example, $\Delta P_b = \Delta P$. Suppose $f = \frac{A_r}{A_b} \cdot K_b \cdot \cos\beta$, therefore:

$$\Delta p = \left(\frac{Q_b}{Q_r}\right)\cdot\left[f\cdot\left(\frac{Q_b}{Q_r}\right) - 2 + \left(\frac{Q_b}{Q_r}\right)\right]\cdot\rho\cdot v_r^2$$

After transposition, then:

$$(1+f)\times\left(\frac{Q_b}{Q_r}\right)^2 - 2\times\left(\frac{Q_b}{Q_r}\right) - \frac{\Delta p}{\rho\cdot v_r^2} = 0$$

The above formula is the quadratic formula of (Q_b/Q_r).

By

$$\frac{\Delta p}{\rho\cdot v_r^2} = \frac{155.75}{1.2\times7.67^2} = 2.21$$

and

$$f = \frac{A_r}{A_b}\cdot K_b\cdot\cos\beta = \frac{63.85}{12}\times0.9\times1.0 = 4.79$$

$Q_b/Q_r = 0.816$, therefore,

$$Q_b = Q_r\times0.816 = 490\times0.816 \approx 400\text{m}^3/\text{s}$$

[By checking that $v_1 = \frac{490-400}{63.85-12} = 1.74\text{m/s} < \frac{1}{2}\times7.67\text{m/s}$

$$\zeta_e\cdot\frac{\rho}{2}\cdot v_1^2 = 0.6\times0.6\times1.74^2 = 1.09\text{N/m}^2$$

Therefore, the assumption of $\upsilon_1 = 0.5\upsilon$ is reliable and more trial is unnecessary.]

② Calculation of air inlet area (let the air velocity at air inlet to be 30m/s)

In $\Delta p_b = \Delta p = 2\left(\frac{Q_b}{Q_r}\right)\left[\frac{K_b \cdot v_b \cdot \cos\beta}{v_r} - 2 + \left(\frac{Q_b}{Q_r}\right)\right] \cdot \frac{\rho}{2} \cdot v_r^2$,

Given $\upsilon_b = 30$m/s, by

$$\frac{K_b \cdot v_b \cdot \cos\beta}{v_r} = \frac{0.9 \times 30 \times 1.0}{7.67} = 3.52$$

$$\frac{\Delta P}{\frac{\rho}{2} \cdot v_r^2} = \frac{155.75}{0.6 \times 7.67^2} = 4.41$$

$$\left(\frac{Q_b}{Q_r}\right)^2 + 1.52\left(\frac{Q_b}{Q_r}\right) - \frac{4.41}{2} = 0$$

$$Q_b/Q_r = 0.908, Q_b = 490 \times 0.908 = 444.92\text{m}^3/\text{s}$$

$$A_b = Q_b/v_j = 444.92/30 = 14.83\text{m}^2$$

[By checking that $v_1 = \frac{490 - 444.92}{63.85 - 14.83} = 0.92\text{m/s} < \frac{1}{2} \times 7.67\text{m/s}$

Therefore, the assumption of $\upsilon_1 = 0.5\upsilon_r$ is reliable and more trial is unnecessary.]

(4) Design of air supply fan power

On the basis of calculation in item (3), the power cost and engineering construction cost (including fan, ventilation tower, duct and so on) are analyzed and compared so as to choose the most appropriate air supply fan.

Rewrite formula (7.6.5-3) and let Δp_d to be 300N/m^2, therefore:

For sub-item① under item (3) ($Q_b = 400\text{m}^3/\text{s}$, $\upsilon_b = 33.33$m/s):

$$p_{tot} = 1.1 \times \left(\frac{\rho}{2} \cdot v_b^2 + \Delta p_d\right) = 1.1 \times (0.6 \times 33.33^2 + 300) = 1\,063.19\text{N/m}^2$$

The total-pressure output power of axial fan is:

$$S_{th} = \frac{Q_b \times P_{tot}}{1000} = \frac{399 \times 1063.19}{1000} = 425.3\text{kW}$$

Given the efficiency of air supply fan $\eta_f = 0.8$, then its total-pressure input power S_{kw} is:

$$S_{kw} = \frac{S_{th}}{\eta_f} = \frac{425.3}{0.8} = 531.6\text{kW}$$

For sub-item② under item (3) ($Q_b = 444.92\text{m}^3/\text{s}, \upsilon_b = 30\text{m/s}$):

$$P_{tot} = 1.1 \times \left(\frac{\rho}{2} \cdot v_b^2 + \Delta P_d \right) = 1.1 \times \left(0.6 \times 30^2 + 300 \right) = 924\text{N/m}^2$$

$$S_{kw} = \frac{444.92 \times 924}{1000 \times 0.8} = 513.9\text{kW}$$

The results show that the power cost difference in this example is a little, which means the engineering construction cost is a main factor for economy consideration.

Example E-3 Longitudinal ventilation with supply and exhaust shafts (with one ventilation shaft)

(1) Calculation conditions of tunnel

Traffic direction	Uni-directional traffic
Tunnel length	$L = 4\,100\text{m}$ ($L_1 = 2\,000\text{m}$, $L_2 = 2\,100\text{m}$)
Sectional area of tunnel	$A_r = 66.04\text{m}^2$
Hydraulic diameter of cross section	$D_r = 8.25\text{m}$
Design PHV of hybrid vehicles	$N = 1,850\text{veh./h}$
Ratio of large vehicles	$r_l = 55\%$ ($A_m = 3.43\text{m}^2$)
Ratio of diesel vehicles	$r_d = 28\%$
Ventilation air velocity	$\upsilon_t = 80\text{km/h} = 22.22\text{m/s}$
Required air volume flow in the tunnel	$Q_{req} = 756\text{m}^3/\text{s}$ ($Q_{req\,I} = 396$, $Q_{req\,II} = 360$)
Natural air velocity in tunnel	$\upsilon_n = 1.5\text{m/s}$

(2) Supply air volume flow, exhaust air volume flow, concentration, pressure rise and design air velocity

By

$$Q_b = Q_{req} - Q_{r1} + Q_e \cdot \left(\frac{Q_{r1} - Q_{req1}}{Q_{r1}} \right)$$

$$\Delta p_e = 2 \cdot \frac{Q_e}{Q_{r1}} \cdot \left(2 - \frac{v_e \cdot \cos\alpha}{v_{r1}} - \frac{Q_e}{Q_{r1}} \right) \cdot \frac{\rho}{2} \cdot v_{r1}^2$$

$$\Delta p_b = 2 \cdot \frac{Q_b}{Q_{r2}} \cdot \left(\frac{K_b \cdot v_b \cdot \cos\beta}{v_{r2}} - 2 + \frac{Q_b}{Q_{r2}} \right) \cdot \frac{\rho}{2} \cdot v_{r2}^2$$

Given $\upsilon_b = 28\text{m/s}$, $\upsilon_e = 6\text{m/s}$, $\beta = 0°$ ($\cos\beta = 1.0$), $K_b = 1.0$ and $K_e = 0.9$, calculate with the values listed in Table E-1 (perform trial calculation in tables respectively).

Table E-1 Calculation of pressure rise Δp_e and Δp_b (given $Q_e = 340m^3/s$)

v_{r1}	6.0	6.5	7.0	7.5	8.0	备注
Q_{r1}	396	429	462	495	528	
$\rho/2 \cdot v_{r1}^2$	22.03	25.86	29.99	34.43	39.17	
v_e/v_{r1}	1.0	0.923	0.857	0.80	0.75	
Q_e/Q_{r1}	0.859	0.793	0.736	0.687	0.644	
Δp_e	9.12	15.43	21.75	28.05	34.36	
Q_b	360	358	351	340	327	$Q_{r2} = Q_b - Q_e + Q_{r1}$ $v_{r2} = Q_{r2}/A_r$
Q_{r2}	416	447	473	495	515	
v_{r2}	6.302	6.769	7.162	7.495	7.800	
$\rho/2 \cdot v_{r2}^2$	24.31	28.04	31.39	34.38	37.24	
v_b/v_{r2}	4.443	4.136	3.909	3.736	3.59	
Q_b/Q_{r2}	0.865	0.801	0.742	0.687	0.635	
Δp_b	139.1	131.9	123.5	114.4	105.2	

The following values are calculated after analysis:

$$Q_e = 340m^3/s; Q_{r1} = 396m^3/s; v_{r1} = 6.0m/s;$$

$$Q_b = 360m^3/s; Q_{r2} = 416m^3/s; v_{r2} = 6.3m/s。$$

$\Delta p_b + \Delta p_e = 139.1 + 9.12 = 148.22N/m^2$ (pressure rise at air outlet / air inlet). It is checked that:

$$C_2 = \frac{Q_{req1}}{Q_{r1}} = \frac{396}{396} = 1.0$$

$$C_3 = \frac{Q_{req2}}{Q_{r1} - Q_e - Q_{req1} + \dfrac{Q_e \cdot Q_{req1}}{Q_{r1}} + Q_b} = 1.0$$

$$\frac{Q_e}{Q_{r1}} = 0.859 < 1.0; \qquad \frac{Q_b}{Q_{r2}} = 0.865 < 1.0$$

so, it is satisfactory.

$$Q_s = Q_{r1} - Q_e = 396 - 340 = 56m^3/s$$

$$v_{rs} = \frac{Q_s}{A_r} = \frac{56}{66.04} = 0.85m/s$$

That is, airflow in the short duct flows at a low speed.

(3) Pressure demand in tunnel Δp

Pressure demand in tunnel Δp shall be the sum of pressure demands in Zone I and Zone II, that is:

$$\begin{aligned}\Delta p &= \Delta p_r - \Delta p_t + \Delta p_m \\ &= (\Delta p_{r1} + \Delta p_{r2}) - (\Delta p_{t1} + \Delta p_{t2}) + \Delta p_m\end{aligned}$$

When calculating the ventilation resistance Δp_r, for Zone I, flow loss at the exit is zero; for Zone II, pressure loss at the entrance is zero. The loss of ventilation shaft bifurcation shall be considered and the loss coefficient is set to $\zeta_{bifurcation} = 0.28$. When calculating the piston effect of traffic Δp_t, with consideration to unfavorable cases and for the sake of safety, let $\upsilon_t = 50\text{km/h} = 13.89\text{m/s}$. When calculating natural wind resistance Δp_m, let loss coefficient at the air inlet $\zeta_{interflow} = 0.7$ and natural air velocity in tunnel $\upsilon_n = 1.5\text{m/s}$.

$$\begin{aligned}\Delta p_{r1} &= \left(\zeta_{入口} + \lambda \cdot \frac{L_1}{D_r}\right) \cdot \frac{\rho}{2} \cdot v_{r1}^2 + \zeta_{分岔} \cdot \frac{\rho}{2} \cdot v_{r1}^2 \\ &= \left(0.28 + 0.6 + 0.0255 \times \frac{2\,000}{8.25}\right) \times 0.6 \times 6.0^2 = 155.6\text{N/m}^2\end{aligned}$$

$$\begin{aligned}\Delta p_{r2} &= \left(1 + \lambda \cdot \frac{L_2}{D_r}\right) \cdot \frac{\rho}{2} \cdot v_{r2}^2 + \zeta_{合流} \cdot \frac{\rho}{2} \cdot v_{r2}^2 \\ &= \left(1 + 0.7 + 0.0255 \times \frac{2\,100}{8.25}\right) \times 0.6 \times 6.3^2 = 199.0\text{N/m}^2\end{aligned}$$

$$\begin{aligned}\Delta p_{t1} &= \frac{A_m}{A_r} \cdot \frac{\rho}{2} \cdot n_{C1} \cdot (v_t - v_{r1})^2 \\ &= \frac{3.43}{66.04} \times 0.6 \times \frac{1\,850 \times 2\,000}{3\,600 \times 13.89} \times (13.89 - 6.0)^2 \\ &= 122.0\text{N/m}^2\end{aligned}$$

$$\begin{aligned}\Delta p_{t2} &= \frac{A_m}{A_r} \cdot \frac{\rho}{2} \cdot n_{C2} \cdot (v_t - v_{r2})^2 \\ &= \frac{3.43}{66.04} \times 0.6 \times \frac{1\,850 \times 2\,100}{3\,600 \times 13.89} \times (13.89 - 6.3)^2 \\ &= 118.5\text{N/m}^2\end{aligned}$$

$$\begin{aligned}\Delta p_m &= \left(1 + \zeta_{入口} + \zeta_{合流} + \zeta_{分岔} + \lambda \cdot \frac{L}{D_r}\right) \cdot \frac{\rho}{2} \cdot v_n^2 \\ &= \left(1 + 0.6 + 0.7 + 0.28 + 0.0255 \times \frac{4\,100}{8.25}\right) \times 0.6 \times 1.5^2 \\ &= 21.0\text{N/m}^2\end{aligned}$$

Pressure demand in tunnel Δp is:

$$\Delta P = 155.6 + 199.0 - 122.0 - 118.5 + 21.0 = 135.1\text{N/m}^2$$

$$\Delta P_b + \Delta P_e = 148.22\text{N/m}^2 > \Delta P_r - \Delta P_t + \Delta P_m = 135.1\text{N/m}^2$$

Thus, it has met the pressure requirement.

(4) Sectional area and short duct length of the air inlet and air outlet

According to engineering practice, the sectional area of air inlet (A_b) should be around $12m^2$ and that of air outlet shall not be larger than that of main tube.

With the above calculations, then:

$$A_b = \frac{Q_b}{v_b} = \frac{360}{28} = 12.8m^2; \qquad A_e = \frac{Q_e}{v_e} = \frac{340}{6} = 56.7m^2$$

The values are consistent with the pressure requirements.

For the prevention of backflow and pollution, the length of short duct shall be appropriate, neither too short nor too long. With consideration to other factors (such as tunnel structure, on-way loss of air pressure and others), the length of short duct in this example L_D is 56m, $q_{VI} = 2.5m^2/$ (vehicle · km), $K = 0.007$ and $f_{iv} = 1.3$, therefore:

$$q_0 = \frac{q_{VI}}{3\,600K} = 0.099\,2m^3/s$$

$$Q_{req/s} = q_0 \cdot N \cdot ds \cdot f_{iv} = 0.099\,2 \times 1\,850 \times 0.056 \times 1.3$$

$$= 13.36m^3/s$$

$$C_2 = \frac{Q_{req/s}}{Q_s} = \frac{13.36}{56} = 0.24$$

The concentration distribution of this example is shown in Figure E-2 (concentration variation in short duct is ignored here).

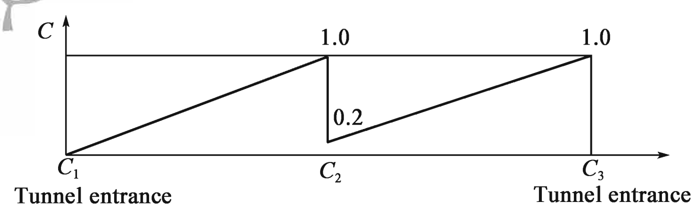


Figure E-2 Concentration distribution

Example E-4 Longitudinal ventilation with supply and exhaust shafts + jet fan

(1) Calculation conditions of tunnel

Traffic direction	uni-directional traffic
Tunnel length	$L = 3,922m$ ($L_1 = 1,972m$, $L_2 = 1,950m$)
Sectional area of tunnel	$A_r = 59.5m^2$

Hydraulic diameter of cross section $D_r = 7.79\text{m}$
Design PHV of hybrid vehicles $N = 1656\text{veh./h}$
Ratio of large vehicles $r_l = 70\%$ ($A_m = 4.08\text{m}^2$)
Ratio of diesel vehicles $r_d = 42\%$
Ventilation air velocity $\upsilon_t = 60\text{km/h} = 16.67\text{m/s}$
Required air volume flow $Q_{req} = 700.08\text{m}^3/\text{s}$ ($Q_{req\,1} = 339.91$, $Q_{req\,2} = 360.17$)
Natural air velocity in tunnel $\upsilon_n = 1.0\text{m/s}$

(2) Supply air volume flow, exhaust air volume flow, concentration, pressure rise and design air velocity

By

$$Q_b = Q_{req} - Q_{r1} + Q_e \cdot \left(\frac{Q_{r1} - Q_{req1}}{Q_{r1}}\right)$$

$$\Delta p_e = 2 \cdot \frac{Q_e}{Q_{r1}} \cdot \left(2 - \frac{K_e \cdot v_e}{v_{r1}} - \frac{Q_e}{Q_{r1}}\right) \cdot \frac{\rho}{2} \cdot v_{r1}^2$$

$$\Delta p_b = 2 \cdot \frac{Q_b}{Q_{r2}} \cdot \left(\frac{K_b \cdot v_b \cdot \cos\beta}{v_{r2}} - 2 + \frac{Q_b}{Q_{r2}}\right) \cdot \frac{\rho}{2} \cdot v_{r2}^2$$

Given $\upsilon_b = 28\text{m/s}$, $\upsilon_e = 6\text{m/s}$, $\beta = 0°$ ($\cos\beta = 1.0$), $K_b = 1.0$ and $K_e = 0.9$, calculate with the values listed in Table E-2 (perform trial calculation in tables respectively).

Table E-2 Calculation of pressure rise Δp_e and Δp_b (given $Q_e = 280\text{m}^3/\text{s}$)

v_{r1}	5.0	5.5	6.0	6.5	7.0	7.5
Q_{r1}	297.5	327.2	357.0	386.8	416.5	446.3
$\rho/2 \cdot v_{r1}^2$	15.00	18.15	21.60	25.35	29.4	33.75
v_e/v_{r1}	1.20	1.09	1.0	0.92	0.86	0.80
Q_e/Q_{r1}	0.941	0.856	0.784	0.724	0.672	0.627
Δp_e	−0.593	5.039	10.703	16.343	21.992	29.130
Q_b	362.7	362	356.5	347.2	335.1	320.5
Q_{r2}	380.2	409.2	433.5	454	471.6	486.8
v_{r2}	6.39	6.88	7.29	7.63	7.93	8.18
$\rho/2 \cdot v_{r2}^2$	24.50	28.40	31.89	34.93	37.73	40.15
v_b/v_{r2}	4.38	4.07	3.84	3.67	3.53	3.42
Q_b/Q_{r2}	0.954	0.885	0.822	0.765	0.711	0.658
Δp_b	155.85	148.54	139.56	130.13	120.23	109.80
$\Delta p_b + \Delta p_e$	155.26	153.58	150.26	146.47	142.22	138.93

The following values are calculated after analysis:

$$Q_e = 280.0\text{m}^3/\text{s}; Q_{r1} = 357.0\text{m}^3/\text{s}; v_{r1} = 6.0\text{m/s};$$

$$Q_b = 356.48\text{m}^3/\text{s}; Q_{r2} = 433.48\text{m}^3/\text{s}; v_{r2} = 7.29\text{m/s}。$$

$\Delta p_b + \Delta p_e = 139.56 + 10.70 = 150.26\text{N/m}^2$ (pressure rise at air outlet / air inlet). It is checked that:

$$C_2 = \frac{Q_{req1}}{Q_{r1}} = \frac{339.91}{357.0} = 0.952 < 1.0$$

$$C_3 = \frac{Q_{req2}}{Q_{r1} - Q_e - Q_{req1} + \dfrac{Q_e \cdot Q_{req1}}{Q_{r1}} + Q_b} = \frac{360.17}{360.17} = 1.0$$

$$\frac{Q_e}{Q_{r1}} = \frac{280}{357.0} = 0.784 < 1.0; \quad \frac{Q_b}{Q_{r2}} = \frac{356.48}{433.48} = 0.822 < 1.0$$

so, it is satisfactory.

$$Q_s = Q_{r1} - Q_e = 357.0 - 280.0 = 77.0\text{m}^3/\text{s}$$

$$v_{rs} = \frac{Q_s}{A_r} = \frac{77.0}{59.5} = 1.29\text{m/s}$$

(3) Pressure demand in tunnel Δp

Pressure demand in tunnel Δp shall be the sum of pressure demands in Zone I and Zone II, that is:

$$\begin{aligned}\Delta p &= \Delta p_r - \Delta p_t + \Delta p_m \\ &= (\Delta p_{r1} + \Delta p_{r2}) - (\Delta p_{t1} + \Delta p_{t2}) + \Delta p_m\end{aligned}$$

When calculating the ventilation resistance Δp_r, for Zone I, flow loss at the exit is zero; for Zone II, flow loss at the entrance is zero. The loss of ventilation shaft bifurcation shall be considered and the loss coefficient is set to $\zeta_{\text{bifurcation}} = 0.28$. When calculating the piston effect of traffic Δp_t, with consideration to unfavorable cases and for the sake of safety, let $\upsilon_t = 50\text{km/h} = 13.89\text{m/s}$. When calculating natural wind resistance Δp_m, let loss coefficient at the air inlet $\zeta_{\text{interflow}} = 0.7$ and natural air velocity in tunnel $\upsilon_n = 1.5\text{m/s}$.

$$\begin{aligned}\Delta p_{r1} &= \left(\zeta_{\text{入口}} + \lambda \cdot \frac{L_1}{D_r}\right) \cdot \frac{\rho}{2} \cdot v_{r1}^2 + \zeta_{\text{分岔}} \cdot \frac{\rho}{2} \cdot v_{r1}^2 \\ &= \left(0.28 + 0.6 + 0.025\,5 \times \frac{1\,972}{7.79}\right) \times 0.6 \times 6.0^2 = 155.71\text{N/m}^2\end{aligned}$$

$$\begin{aligned}\Delta p_{r2} &= \left(1 + \lambda \cdot \frac{L_2}{D_r}\right) \cdot \frac{\rho}{2} \cdot v_{r2}^2 + \zeta_{\text{合流}} \cdot \frac{\rho}{2} \cdot v_{r2}^2 \\ &= \left(1 + 0.7 + 0.025\,5 \times \frac{1\,950}{7.79}\right) \times 0.6 \times 7.29^2 = 253.75\text{N/m}^2\end{aligned}$$

$$\Delta p_{t1} = \frac{A_m}{A_r} \cdot \frac{\rho}{2} \cdot n_1 \cdot (v_t - v_{r1})^2$$

$$= \frac{4.08}{59.5} \times 0.6 \times \frac{1\,656 \times 1\,972}{3\,600 \times 13.89} \times (13.89 - 6.0)^2 = 166.42\text{N/m}^2$$

$$\Delta p_{t2} = \frac{A_m}{A_r} \cdot \frac{\rho}{2} \cdot n_2 \cdot (v_t - v_{r2})^2$$

$$= \frac{4.08}{59.5} \times 0.6 \times \frac{1\,656 \times 1\,950}{3\,600 \times 13.89} \times (13.89 - 7.29)^2$$

$$= 115.16\text{N/m}^2$$

$$\Delta p_m = \left(1 + \zeta_{入口} + \zeta_{合流} + \zeta_{分岔} + \lambda \cdot \frac{L}{D_r}\right) \cdot \frac{\rho}{2} \cdot v_n^2$$

$$= \left(1 + 0.6 + 0.7 + 0.28 + 0.025\,5 \times \frac{3\,922}{7.79}\right) \times 0.6 \times 1.0^2$$

$$= 9.10\text{N/m}^2$$

Pressure demand in the tunnel Δp is:

$$\Delta P = 155.71 + 253.75 - 166.42 - 115.16 + 9.10 = 191.58\text{N/m}^2$$

$$\Delta P - (\Delta P_b + \Delta P_e) = 191.58 - (10.70 + 139.56) = 41.32\text{N/m}^2$$

(4) Longitudinal ventilation with supply and exhaust shafts + jet fan

For 900-model jet fan, the pressure rise of each fan $\Delta p_j = 3.99\text{N/m}^2$, therefore, the quantity demand is:

$$i = \frac{41.32}{3.99} = 10.36\text{jet fans}$$

The pressure, air velocity and concentration distribution of this example are shown in Figure E-3 (concentration variation in short duct is ignored here).

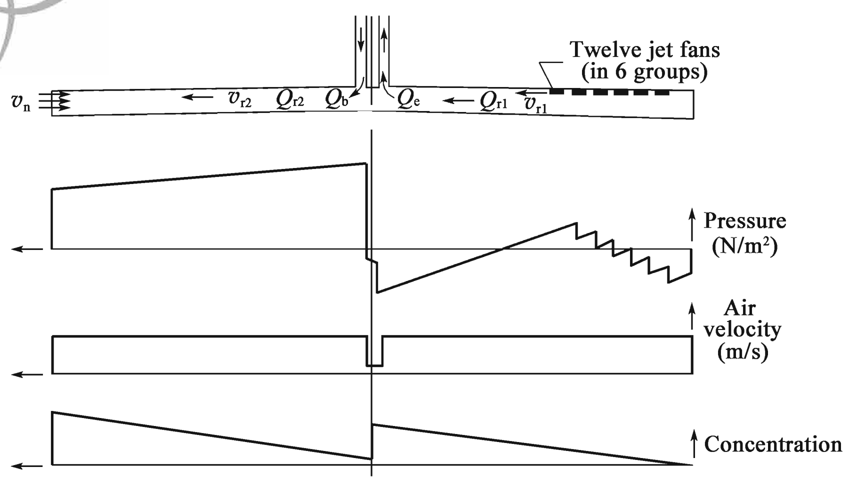


Figure E-3 Pressure, air velocity and concentration distribution

Example E-5 Vacuum longitudinal ventilation mode

(1) Calculation conditions of tunnel

Traffic direction	Uni-directional traffic
Tunnel length	$L = 3,000\text{m}$
Sectional area of tunnel	$A_r = 58.0\text{m}^2$
Hydraulic diameter of cross section	$D_r = 7.7\text{m}$
Design PHV of hybrid vehicles	$N = 1,700\text{veh./h}$
Ratio of large vehicles	$r_l = 43\%$ ($A_m = 2.9\text{m}^2$)
Proportion of diesel vehicle	$r_d = 42\%$
Ventilation air velocity	$\upsilon_t = 60\text{km/h} = 16.67\text{m/s}$
Required air volume flow	$Q_{req(VI)} = 590\text{m}^3/\text{s}$ (particulate matter emission is considered)
	$Q_{req(co)} = 210\text{m}^3/\text{s}$ (carbon monoxide is considered)

(2) Basic determination ofdust collector room position

The required air volume flow of particulate matters is $590\text{m}^3/\text{s}$, which is more than that of carbon monoxide ($210\text{m}^3/\text{s}$), thus, dust collector should be adopted. The ventilation system adopting longitudinal ventilation with dust collector is shown in Figure E-4. Ignoring the pressure rise of dust collector in the first calculation and setting $\Delta p_m = 52\text{N/m}^2$, then the air volume flow into the tunnel due to air velocity at portal (Q_{in}) and the zone length (L_1) can be calculated as follows.

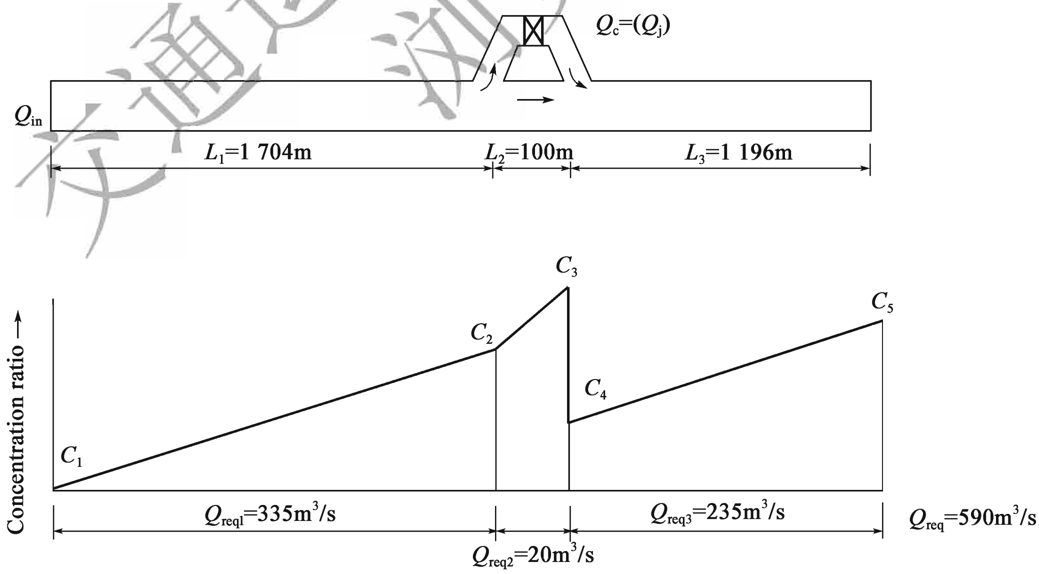


Figure E-4 Sketch of ventilation system adopting vacuum longitudinal ventilation mode

Note: This example strictly calculates the concentration variation between the air inlet center and air outlet center. Although there is variation between such two centers, a simplified calculation without consideration to short duct is acceptable due to turbulent diffusion from driving.

Use above values in the following formula:

$$\left(1+\zeta_{e}+\lambda\cdot\frac{L}{D}\right)_{r}\cdot\frac{\rho}{2}\cdot v_{r}^{2}-\frac{A_{m}}{A_{r}}\cdot n\cdot\frac{\rho}{2}\cdot(v_{t}-v_{r})^{2}+\Delta p_{m}=0$$

Then $$6.804v_{r}^{2}-2.549\,(16.67-v_{r})^{2}+52=0$$

And $$v_{r}=5.95\text{m/s}$$

$$Q_{in}=v_{r}\cdot A_{r}=5.95\times58=345\text{m}^{3}/\text{s}$$

Dust collector should be installed at portal L_1, that is:

$$L_{1}=\frac{345}{590}\times3000=1754\text{m}$$

(3) Calculation of concentration ratio

By the following formula, the rough estimate Q_c of first air volume flow can be worked out:

$$Q_{c}=\frac{\text{Required air volume flow (590) — supply air volume flow (345)}}{\text{VI}_{\text{improvement rate}}\,(0.8)}=306\text{m}^{3}/\text{s}$$

Large-capacitydust collector is suggested. The dust collector room is set at curve tunnel. Set the length of short duct L_2 to 100m, then the concentration ratio of each control point is calculated as follows:

$$C_{1}=0$$

$$C_{2}=\frac{Q_{req1}}{Q_{in}}=\frac{335}{345}=0.97$$

$$C_{3}=C_{2}+\frac{Q_{req2}}{Q_{in}-Q_{c}}=0.97+\frac{20}{345-306}=0.97+0.51=1.48$$

$$C_{4}=\frac{C_{2}\times Q_{c}(1-\eta_{VI})+C_{3}\times(Q_{in}-Q_{c})}{Q_{in}}$$

$$=\frac{0.97\times306\times(1-0.8)+1.48\times(345-306)}{345}=0.34$$

$$C_{5}=C_{4}+\frac{Q_{req3}}{Q_{in}}=0.34+\frac{235}{345}=0.34+0.68=1.02$$

(4) Estimated pressure rise due to air supply volume flow effect

Calculation of pressure rise from air supply ofdust collector can be performed under the longitudinal ventilation with supply and exhaust shafts, that is, Q_c ($=Q_b$) and Q_{in} can be calculated via $\Delta p_{b}=\Delta p_{r}-\Delta p_{t}+\Delta p_{m}$.

(5) Relationship between Q_{in} and concentration distribution

With the concentration formulas in item (3) and Q_c variable, the relationship between concentration at tunnel exit and Q_{in} can be worked out. Given $C_5 = 1.0$, the corresponding Q_c can be worked out. By this, concentration of each point (C) and transmittance of light in particulate matters may be worked out.

Example E-6 Full transverse ventilation mode

(1) Semi-transverse supply ventilation mode

① Calculation conditions of tunnel

Traffic direction	bi-directional traffic
Tunnel length	$L = 2,160\text{m}$
Length of arch duct	$L_b = 1,080\text{m}$ (supply air at two portals)
Sectional area of tunnel	$A_r = 42.0\text{m}^2$
Hydraulic diameter of the tunnel	$D_r = 6.0\text{m}$
Design PHV of hybrid vehicles	$N = 1,428\text{veh./h}$
Ventilation air velocity	$\upsilon_t = 60\text{km/h} = 16.67\text{m/s}$
Required air volume flow	$Q_{req} = 290\text{m}^3/\text{s}$, $q_b = 290/2160 = 0.134\text{m}^3/(\text{s} \cdot \text{m})$
Sectional area of duct	$A_b = 9.0\text{m}^2$
Hydraulic diameter of the duct	$D_b = 2.3\text{m}$
Equivalent air resistance area of vehicle	$A_m = 2.8\text{m}^2$

② Air pressure of duct and tunnel

Air velocity at duct start υ_{bi}:

$$v_{bi} = \frac{Q}{2A_b} = \frac{290}{2 \times 9.0} = 16.11\text{m/s}$$

Dynamic pressure at duct start p_b:

$$p_b = \frac{\rho}{2} \cdot v_{bi}^2 = 0.6 \times 16.11^2 = 155.72\text{N/m}^2$$

Static pressure difference of duct $P_{bi} - P_{b0}$:

$$k_b = \left(\frac{\lambda}{3} \cdot \frac{L}{D_b} - 1\right) = \frac{0.025}{3} \times \frac{1\,080}{2.3} - 1 = 2.91$$

$$p_{bi} - p_{b0} = k_b \cdot \frac{\rho}{2} \cdot v_{bi}^2 = 2.91 \times 155.72 = 453.62\text{N/m}^2$$

Pressure demand at the end ofsupply duct:

$$P_{b0}-P_{r0}=150\text{N/m}^2$$

Air pressure of tunnel:

$$v_r(x)=\frac{q_b}{A_r}\cdot x=\frac{0.134}{42.0}\cdot x=(3.19\times10^{-3})\cdot x$$

$$\alpha=\frac{A_m}{A_r}\cdot\frac{N\cdot L}{v_t\times3\,600}=\frac{2.8}{42}\times\frac{1\,428\times2\,160}{16.67\times3\,600}=3.43$$

When the upline and downline traffic volumes are the same (both are 50%) and $\Delta p_m=0$, let × = 1,080m, therefore:

$$\begin{aligned}p_{rc}-p_r(x)&=\frac{\rho}{2}\cdot\left[\left(\frac{\lambda}{3}\cdot\frac{x}{D_r}+2\right)\cdot v_r^2(x)+\alpha\cdot\frac{x}{L}\cdot v_t\cdot v_r(x)\right]\\&=0.6\left[\left(\frac{0.025}{3}\times\frac{1\,080}{6.0}+2\right)\cdot(3.19\times10^{-3}\times1\,080)^2+\right.\\&\quad\left.3.43\times\frac{1\,080}{2\,160}(16.67\times3.19\times10^{-3}\times1\,080)\right]\\&=84.03\text{N/m}^2\end{aligned}$$

③ Total pressure demand of air supply fan

Let the pressure loss of connecting duct to p_d, the total pressure demand of air supply fan P_{tot} is calculated as follows:

$P_{tot}=1.1\times$ (air pressure of tunnel + pressure demand at the end + static pressure difference of duct + dynamic pressure at duct start + pressure loss of connecting duct) $=1.1\times(84.03+150+453.62+155.72+p_d)=1.1\times(843.4+p_d)\text{N/m}^2$

(2) Full transverse ventilation mode

① Calculation conditions

Tunnel length	$L=3,200$m
Length ofsupply duct and exhaust duct	$L_b=L=1,600$m (exhaust air at both portals)
Design PHV of hybrid vehicles	$N=2,950$veh./h
Ventilation air velocity	$\upsilon_t=60\text{km/h}=16.67\text{m/s}$
Required air volume flow	$Q_{req}=317\text{m}^3/\text{s}$ (volume flow of each duct)
Sectional area ofsupply duct and exhaust duct	$A_b=A_e=16\text{m}^2$
Hydraulic diameter of supply duct and exhaust duct sections	$D_b=3.2$m

② Total air pressure of air supply fan

Air velocity atthe start of supply duct, v_{bi}:

$$v_{bi} = \frac{Q_b}{A_b} = \frac{317}{16} = 19.8\text{m/s}$$

Dynamic pressure at the start of supply duct, p_b:

$$p_b = \frac{\rho}{2} \cdot v_{bi}^2 = 0.6 \times 19.81^2 = 235.5\text{N/m}^2$$

Static pressure difference ofsupply duct, $P_{bi} - P_{b0}$:

$$k_b = \left(\frac{\lambda}{3} \cdot \frac{L}{D_b} - 1\right) = \frac{0.025}{3} \times \frac{1\,600}{3.2} - 1 = 3.17$$

$$p_{bi} - p_{b0} = k_b \cdot \frac{\rho}{2} \cdot v_{bi}^2 = 3.17 \times 235.5 = 746.5\text{N/m}^2$$

Pressure demand at the end ofsupply duct:

$$P_{b0} - P_{r0} = 150\text{N/m}^2$$

The pressure loss of connecting duct ΔP_{bd} must be based on the shape and resistance of each duct, and calculated by formula (7.10.4-3).

Total pressure demand of air supply fan:

$P_{tot} = 1.1 \times$ (air pressure of tunnel + pressure demand at the end of supply duct + static pressure difference of supply duct + dynamic pressure at supply duct start + pressure loss of connecting duct) $= 1.1 \times (0 + 150 + 746.5 + 235.5 + \Delta P_{bd}) = 1.1 \times (1{,}132 + P_{bd})\text{N/m}^2$

③ Total air pressure of exhaust fan

Air velocity at the end of exhaust duct, v_{e0}:

$$v_{e0} = \frac{Q_e}{A_e} = \frac{317}{16} = 19.81\text{m/s}$$

Dynamic pressure at the end of exhaust duct, p_e:

$$p_e = \frac{\rho}{2} \cdot v_{e0}^2 = 0.6 \times 19.81^2 = 235.5\text{N/m}^2$$

Static pressure difference of exhaust duct $P_{ei} - P_{e0}$:

$$k_e = \left(\frac{\lambda}{3} \cdot \frac{L}{D_e} + 2\right) = \frac{0.025}{3} \times \frac{1\,600}{3.2} + 2 = 6.17$$

$$p_{ei} - p_{e0} = k_e \cdot \frac{\rho}{2} \cdot v_{e0}^2 = 6.17 \times 235.5 = 1\,453\text{N/m}^2$$

Pressure demand at the start of exhaust duct:

$$P_{ri} - P_{ei} = 100\text{N/m}^2$$

The pressure loss of connecting duct P_{ed} must be based on the shape and resistance of each duct and calculated by formula (7.10.4-3).

Total pressure demand of exhaust fan:

P_{tot} = 1.1 × (pressure demand at the start of exhaust duct + static pressure difference of exhaust duct-dynamic pressure at the end of exhaust duct + pressure loss of connecting duct) = 1.1 × (100 + 1,453-235.5 + ΔP_{ed}) = 1.1 × (1,318 + ΔP_{ed}) N/m^2

Wording Explanation for the *Guidelines*

1 The strictness in execution of the *Guidelines* is expressed by using the wording as follows：

1）MUST—A very restrict requirement in any circumstances.

2）SHALL—A mandatory requirement in normal circumstances.

3）SHOULD—An advisory requirement.

4）MAY—A permissive condition. No requirement is intended.

2 Expressions used for reference to standards are explained as follows：

The standards for which a year is added to the standard number shall be the specific versions to be used. Otherwise they shall be the latest available versions.