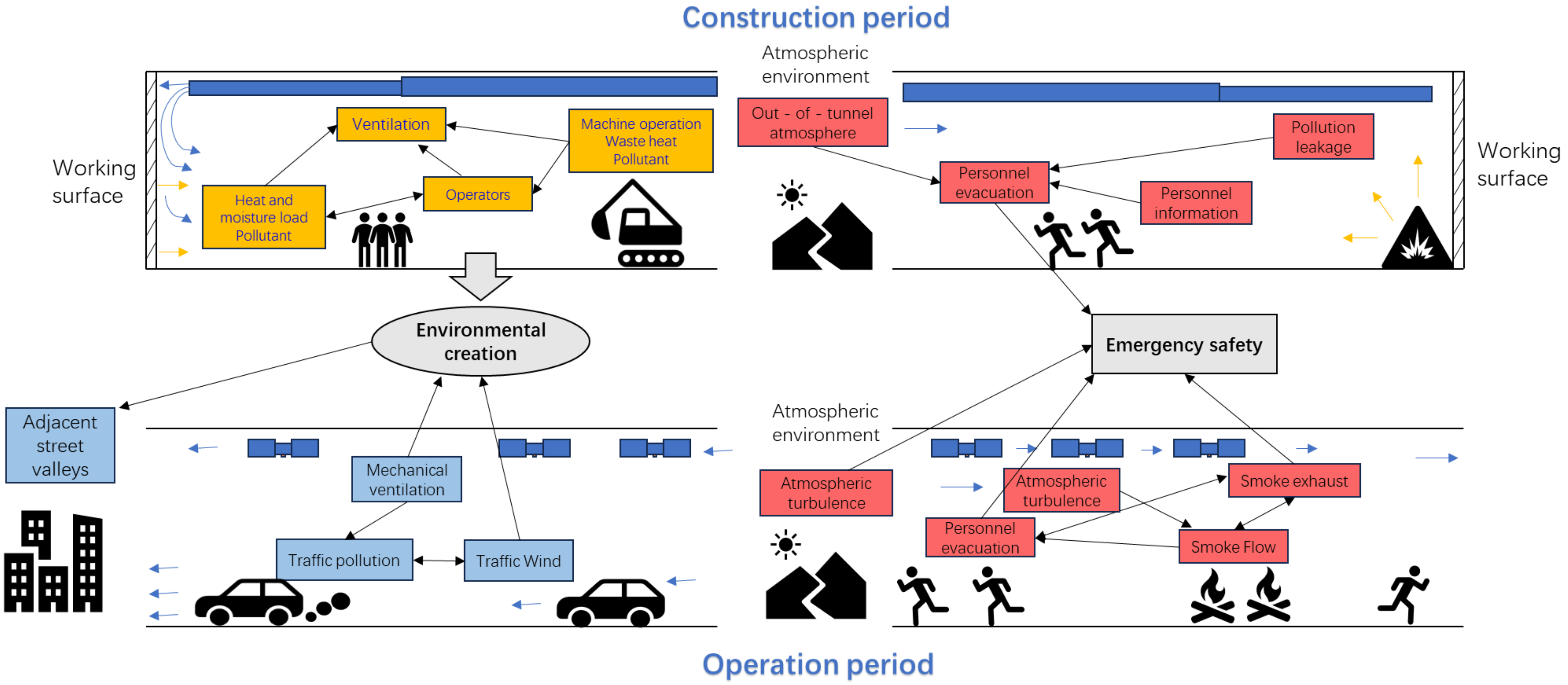
Tunnel Ventilation Engineering

Assoc. Prof. Yu Zhao

2025. 04

Background and Motivation

- Urban tunnels face complex challenges: high pollution, enclosed spaces, and limited evacuation capacity.
- Traditional ventilation and safety systems are outdated and rely on experience-based control.

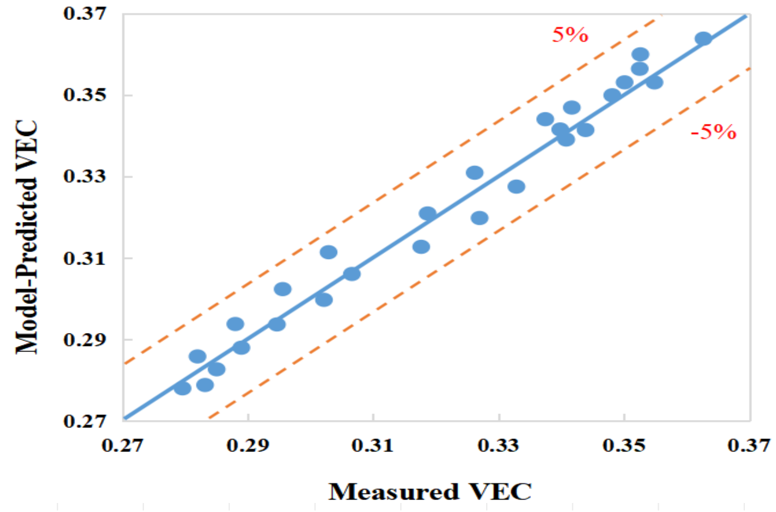


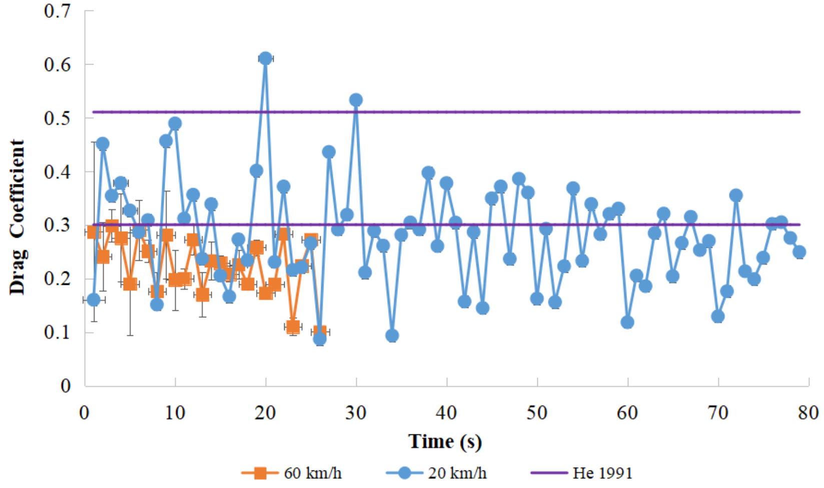
- This project addresses the urgent need for intelligent, lifecycle-based tunnel environmental and safety management.
- Goals include predictive modeling, smart ventilation control, and personalized emergency response systems.

Innovation 1 – Predicting Tunnel Environmental Parameters

High-Accuracy Prediction of Traffic Wind and Pollutant Dynamics

- Developed a high-precision model for tunnel airflow ("traffic wind") and pollutant dispersion.
- Introduced a vehicle canopy theory-based turbulence model validated by wind tunnel tests.
- Proposed a model for ultrafine particle dynamics with over 50% accuracy improvement.





Prediction model of traffic wind and vehicle drag coefficient variation

Wind Tunnel Study – Background and Motivation

- Vehicle-induced turbulence (VIT) plays a major role in pollutant dispersion in tunnels. However, numerical simulations often assume all vehicles have the same height to simplify modeling, which fails to reflect the actual conditions of mixed-height vehicle fleets.

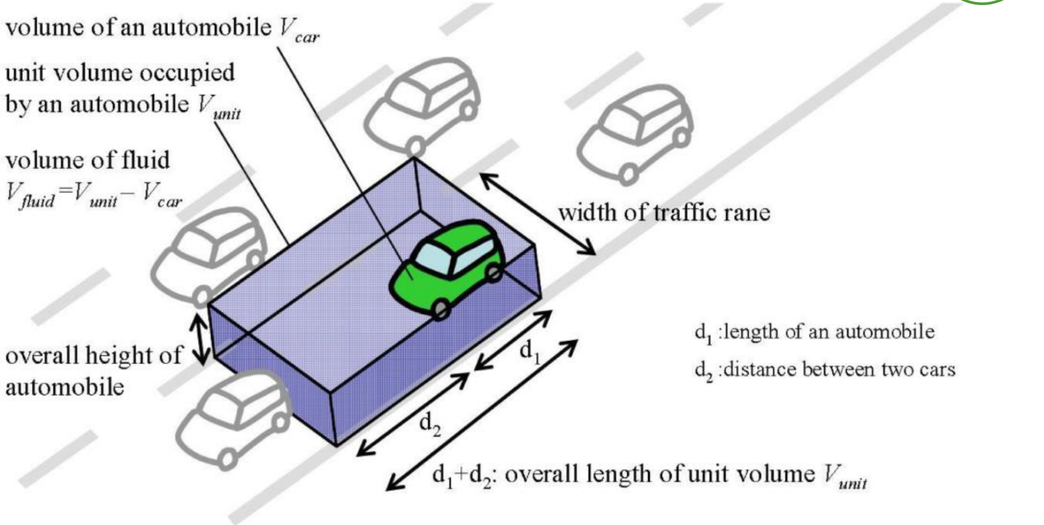
- Modeling each vehicle individually greatly increases computation cost. To address this, we conduct wind tunnel experiments comparing mixed-height and uniform-height fleets. By matching their effects on the wind field, we can determine an equivalent vehicle height, improving simulation efficiency without sacrificing accuracy.

$$\frac{\partial\langle\rho u_i\rangle}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial\langle u_i\rangle}{\partial t} + \langle u_j\rangle\frac{\partial\langle u_i\rangle}{\partial x_j} = -\frac{1}{\rho}\frac{\partial\langle p\rangle}{\partial x_j} + \frac{\partial}{\partial x_j}\left[v\frac{\partial\langle u_i\rangle}{\partial x_j} - \left\langle u_i'.u_j'\right\rangle\right] - F_m \tag{2}$$

$$\frac{\partial\rho k}{\partial t} + \langle u_j\rangle\frac{\partial(\rho k)}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + G_k + G_b - \rho\varepsilon - Y_m + \rho F_k \tag{3}$$

$$\frac{\partial\rho\varepsilon}{\partial t} + \langle u_j\rangle\frac{\partial(\rho\varepsilon)}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial\varepsilon}{\partial x_j}\right] + -\rho C_2\frac{\varepsilon^2}{k+\sqrt{v\varepsilon}} + G_{1\varepsilon}\frac{\varepsilon}{k}C_{3\varepsilon}G_b + \rho F_\varepsilon \tag{4}$$



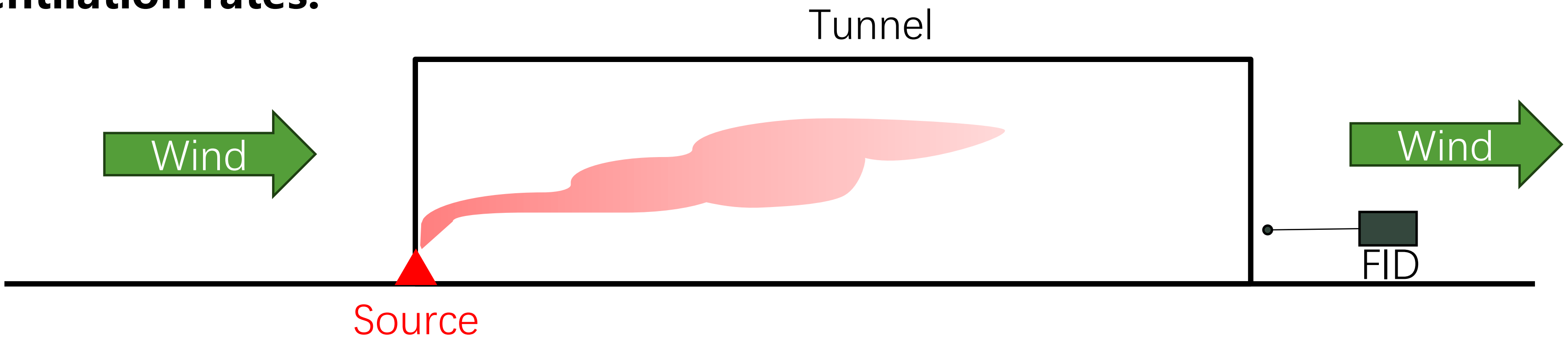
$$F_m = \frac{1}{2}C_{f-car}\frac{A_{car}}{V_{fluid}}\left(\langle u_i\rangle - u_{cari}\right)\sqrt{\left(\langle u_j\rangle - u_{carj}\right)^2} \tag{5}$$

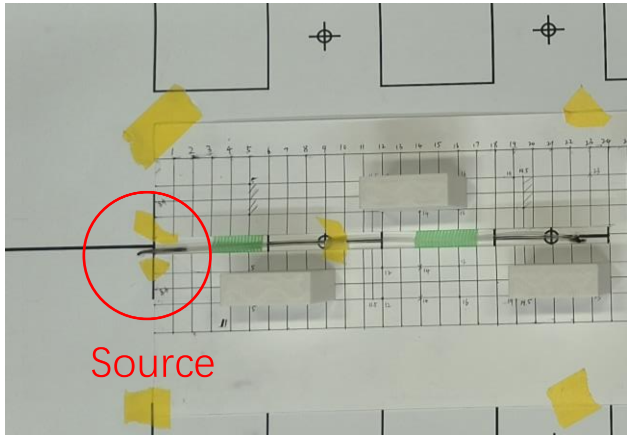
$$F_k = \left(\langle u_i\rangle - u_{cari}\right)F_m \tag{6}$$

$$F_\varepsilon = \frac{\varepsilon}{k}\frac{k^{3/2}}{L_{car}}C_{\varepsilon-car} \tag{7}$$

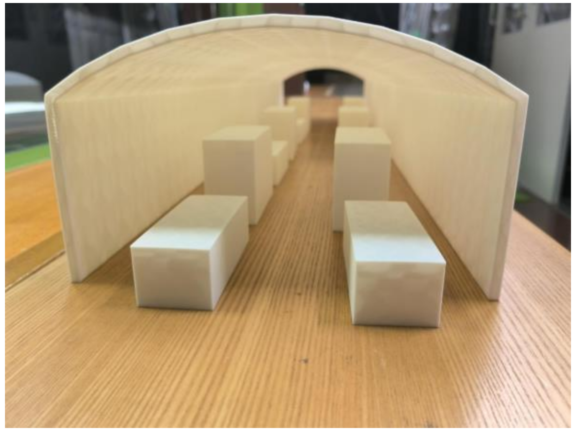
Wind Tunnel Study – Methodology

- Using wind tunnel experiments, we investigated the impact of vehicle-related factors on tunnel ventilation rates.

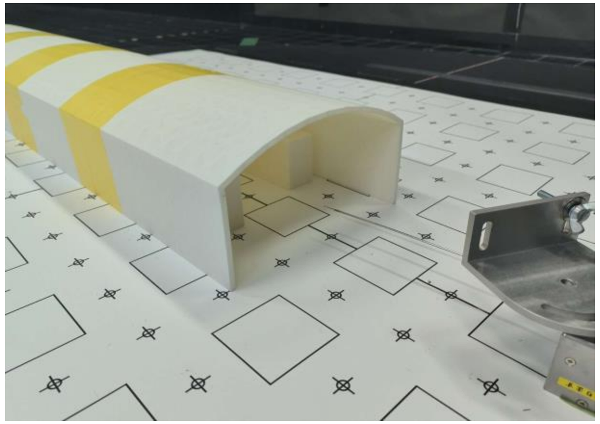




Introducing tracer gases at the tunnel entrance



Setting up different fleet models within the tunnel

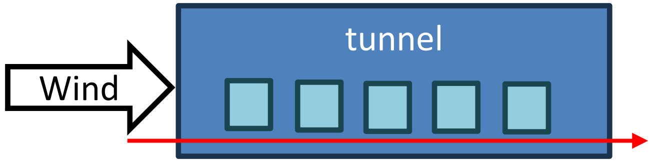


Measuring tracer gas concentrations at the tunnel exit

Wind Tunnel Study – Cases and Results

- Cases can be divided into two groups: investigate the impact of single-height fleets and mixed-height fleets on tunnel ventilation.

Group 1

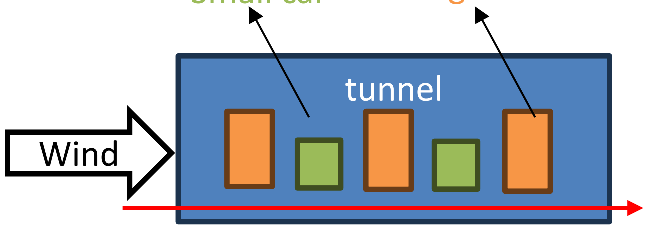


Single height fleet
(The height is variable)

For example

h=1.5cm
h=1.6cm
h=1.7cm
h=1.8cm
……
h=3.0cm

Group 2

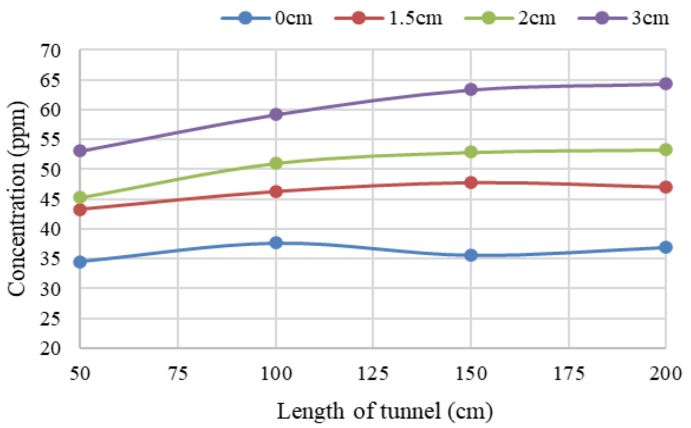


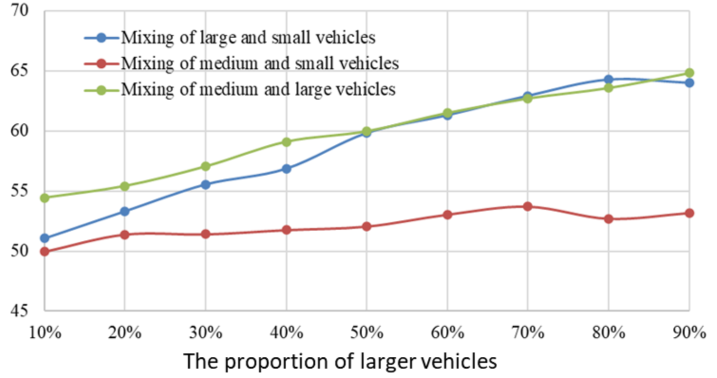
Mixed height fleet

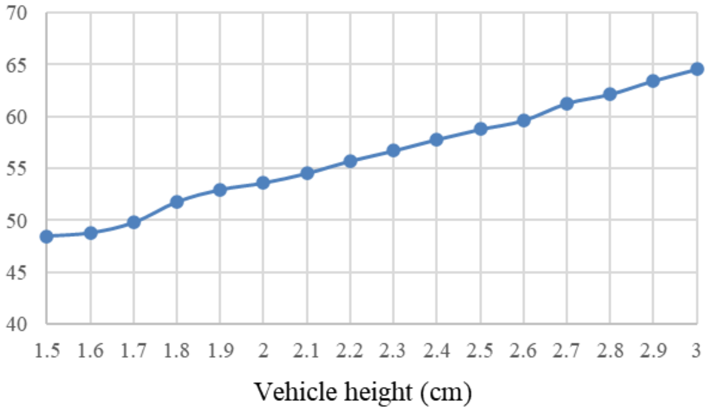
For example

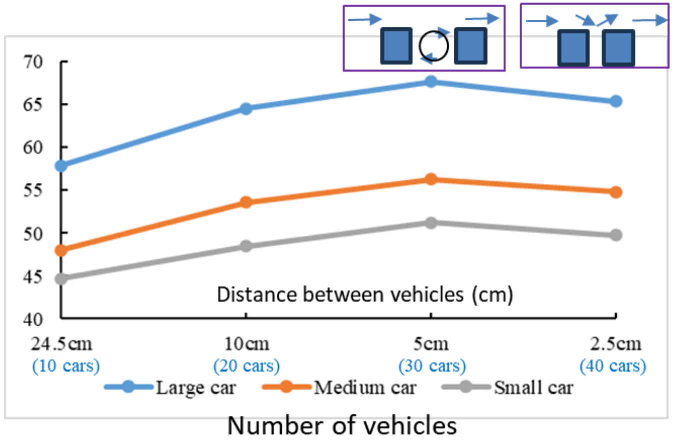
h=3.0cm

h=1.5cm









- The vehicle-related factors we considered included tunnel length, vehicle height, proportion, and vehicle number.

Wind Tunnel Study – Key Findings and VEC Prediction

- A multiple linear regression model was established:

  $VEC = -0.371AH^{*} - 0.091SD^{*} - 0.008VR - 0.019VS^{*} + 0.584$

  (R^2 = 0.96). Prediction error was within 5%.

- The equivalent average height of mixed convoys was estimated as:

  $VH^{*} = 0.979AH^{*} + 0.24SD^{*} + 0.039$.

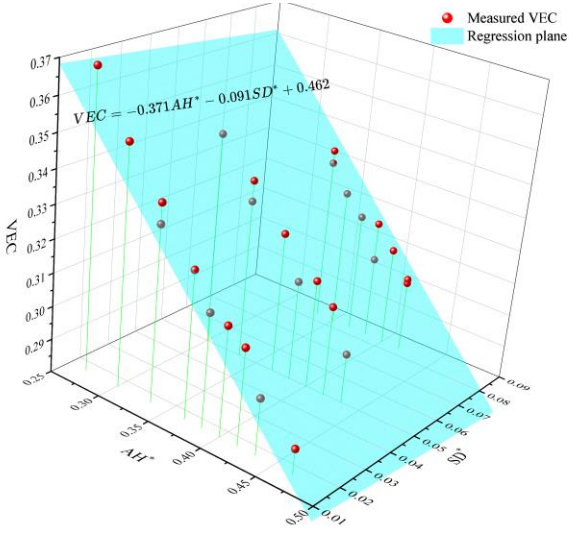
  This allows simplified modeling using uniform-height fleets, significantly reducing computation time.

- Combined with pressure loss equations：

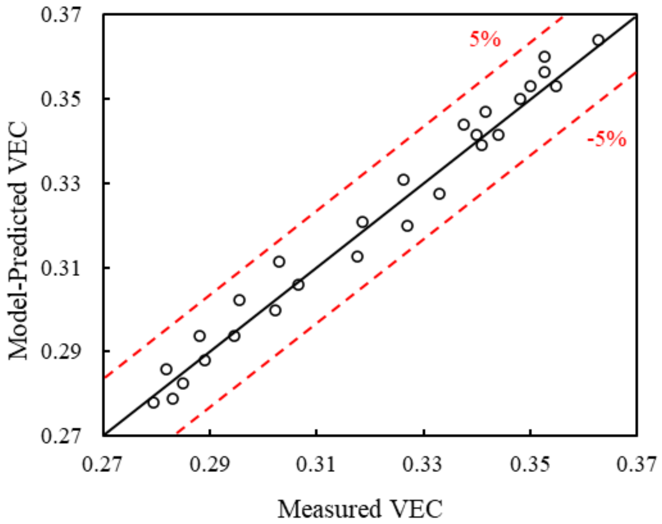
  $$\Delta P = 0.5\,\rho\,(1 - VEC^{2})\,U_H^{2}$$

  This supports improved tunnel ventilation design.

Where VEC is the tunnel ventilation efficiency coefficient, AH* is the average height of vehicles in the convoy, SD* is the height variation, VR is the number of vehicle rows, VS* is the vehicle spacing ratio (spacing divided by vehicle length), and ΔP is the pressure difference caused by the vehicle convoy.



Multiple linear regression plane for VEC based on AH* and SD*



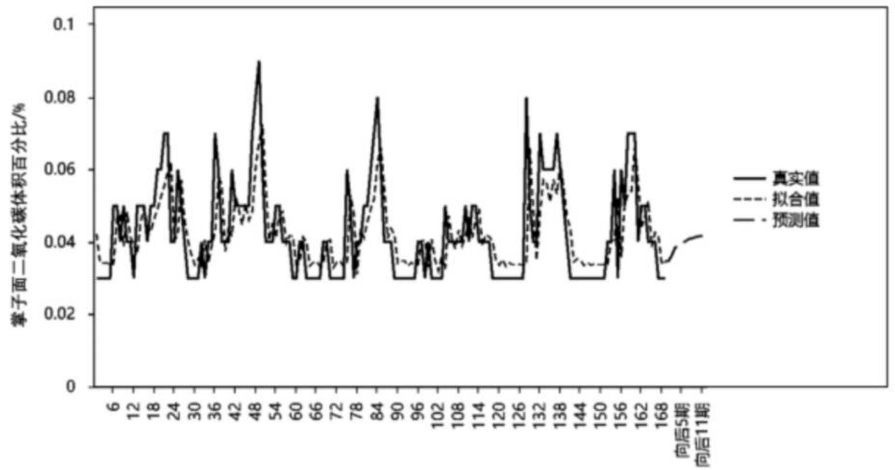
Comparison of model-predicted and measured VEC

Innovation 1 – Construction and Operation Phase Models

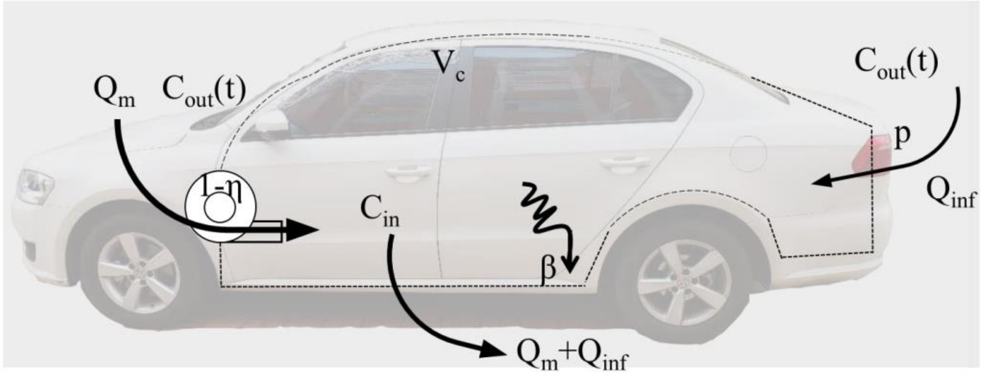
Rapid Spatiotemporal Identification of Environmental Parameters

- ARIMA and CFD-based models for time-space prediction of heat, humidity, and pollutants during construction. Both models achieved <10% error compared to field data.

- Proposed a tunnel-vehicle air quality coupling model to capture non-uniform pollutant behavior during operation. Validated with full-year monitoring from Dalian tunnels; fitting accuracy $R^2 = 0.95$.



Time series prediction model of typical pollutants



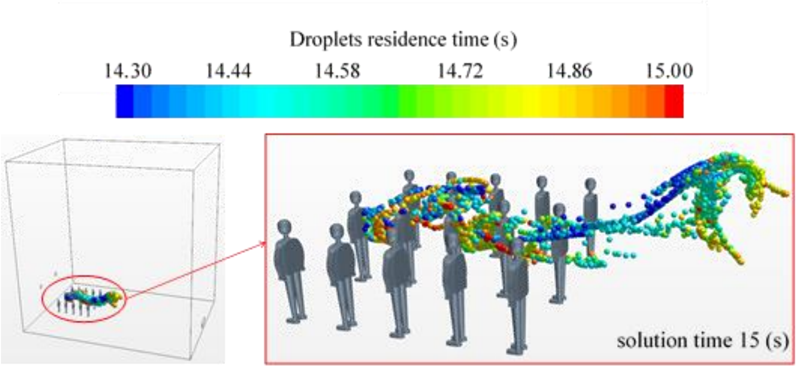
$$C_{in} = f\left(D + p\frac{Q_{inf}}{V_c}C_{out}\Delta t e^{(\eta\frac{Q_{rc}}{V_c}+\frac{Q_{inf}}{V_c}+\beta)\Delta t}\right)e^{-(\eta\frac{Q_{rc}}{V_c}+\frac{Q_{inf}}{V_c}+\beta)\Delta t} + f_0$$

Tunnel–vehicle pollutant coupling diffusion model

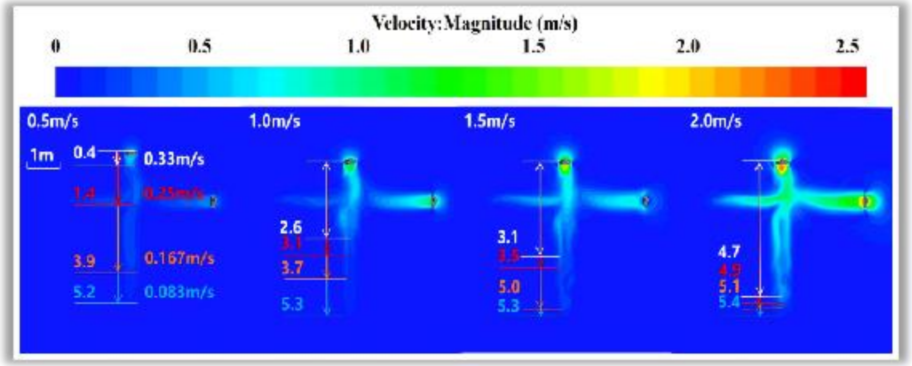
Innovation 2 – Human Activity and Pollutant Spread

Modeling Pollutant Dispersion under Human Movement

- Built a fast, accurate model for pollutant spread under human activity like sitting, walking, sneezing. Model is fast and accurate, with <10% error vs. subway, airport, and campus measurements.
- Introduced turbulence quantification for human movement affecting airflow and pollutant dispersion.



Spatiotemporal pollutant models under various human scenarios



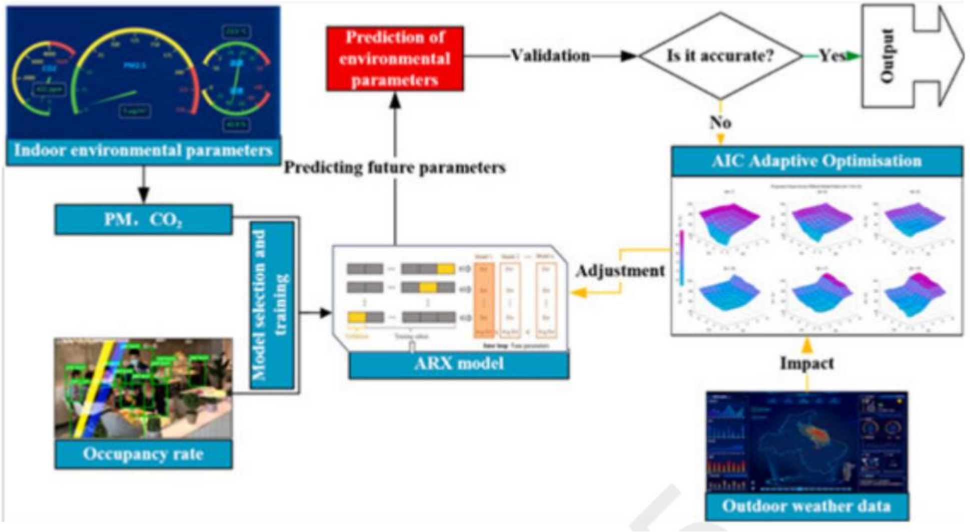
Flow field analysis from pedestrian movement

Innovation 2 – Evacuation Optimization and Smoke Control

Personalized Evacuation Planning under Complex Conditions

- Proposed a dynamic evacuation algorithm considering human movement and environmental factors.
- Combined YOLO-based person detection with real-time flow recognition and environmental occupancy.
- Generated optimized escape routes under constraints like toxic gas spread and random crowd distribution.

Fire-based evacuation simulation



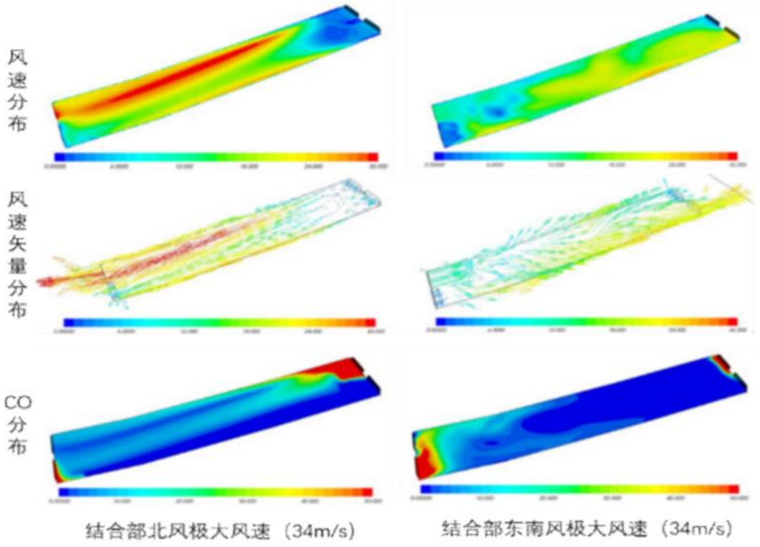
YOLOv5 network structure for human detection

Innovation 3 – Tunnel-Street Canyon Interaction

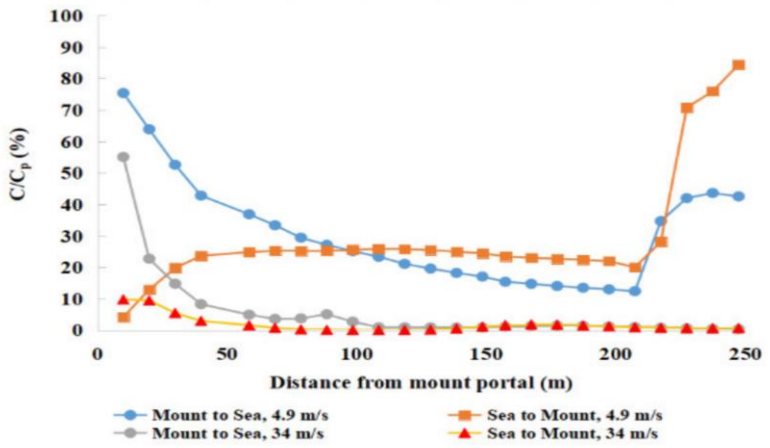
Pollution Dispersion Modeling for Tunnel Outlets and Exhaust Towers

- Proposed a high-precision model for pollution spread from tunnel portals and exhaust towers in urban clusters. Considered combined effects of vehicle-induced and atmospheric turbulence with surrounding terrain and structural factors.

- Suggested optimized emission strategy: improving efficiency by 40%, reducing energy by 20%. Applied in Dalian Bay and Taizishan tunnel projects (>8 km total length).



Wind and pollution fields near tunnel complexes

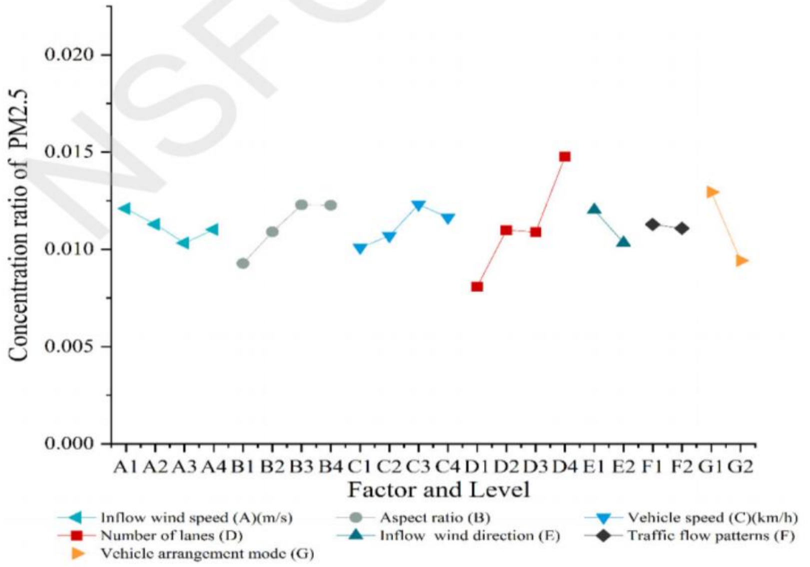


Pollutant spread under varying wind directions

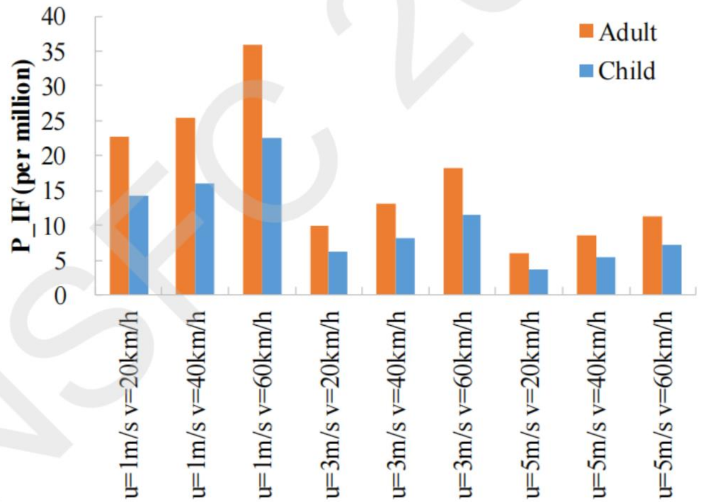
Innovation 3 – Urban Microclimate Risk Modeling

High-Resolution Modeling of Street Canyons

- Developed a fast prediction model for key street canyon parameters under dominant influencing factors. Quantified the effects of aspect ratio, vehicle layout, traffic pattern, and wind conditions on heat and pollutant dispersion.
- Model applied to major roads in Dalian; response time only 10 seconds with much higher accuracy than Gaussian models.



Prediction model for key urban parameters

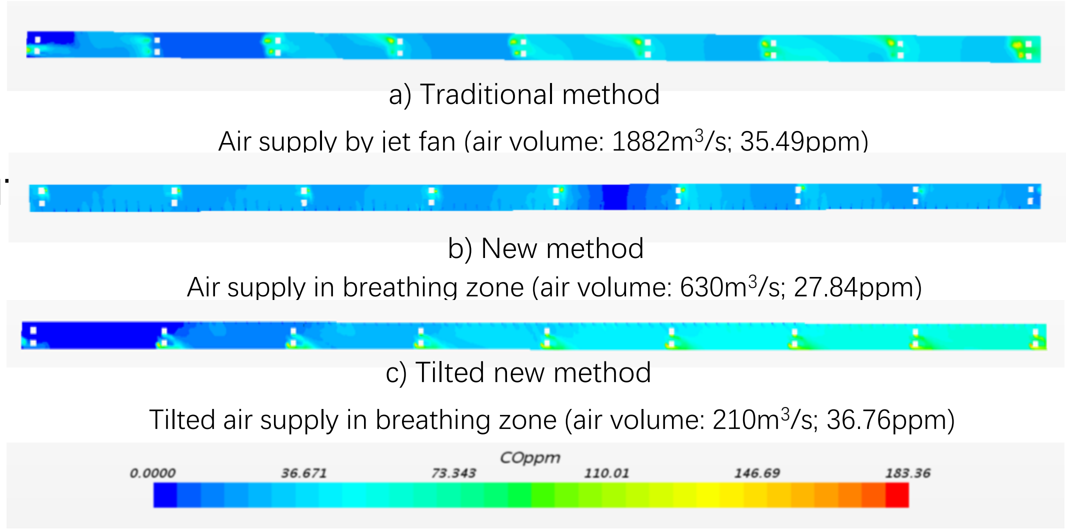


NOx exposure risks in street canyons

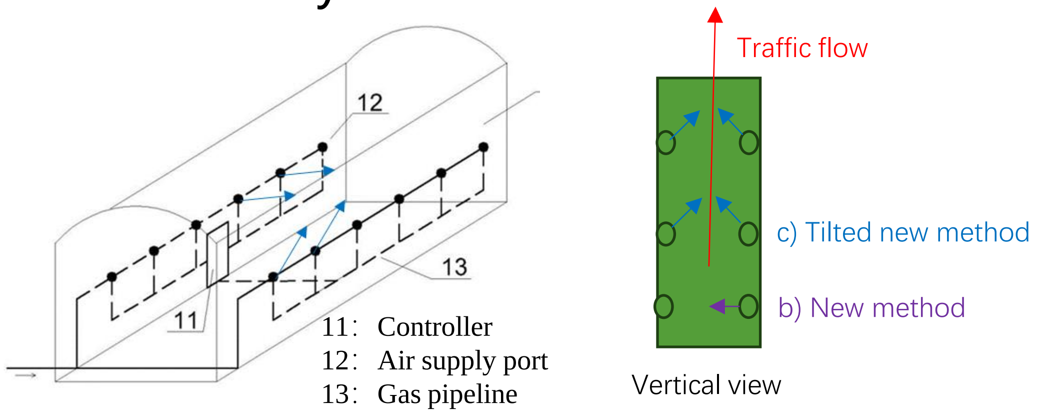
Engineering Applications – New Systems and Technologies

New Systems for Tunnel Construction and Operation

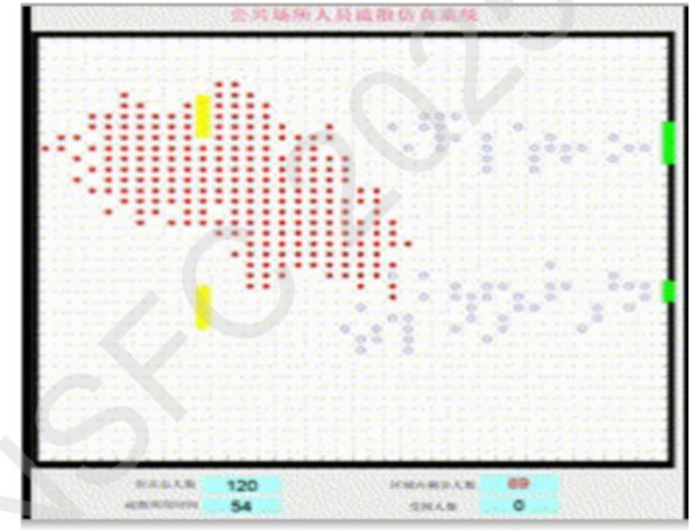
- Developed oxygen-enriched systems for construction to cu
  energy and improve safety.
- Breathing-zone ventilation reduced energy use by 67%.
- Emergency ventilation-escape decoupling improved
  survival rates by 20%.



Breathing-zone ventilation comparison



Oxygen-enriched ventilation system principle



Tunnel evacuation simulation platform

Engineering Applications – Deployment and Benefits

Technology Transfer and Practical Achievements

- Signed four technology transfer contracts totaling ¥2.75 million. Generated over ¥10 million in total economic benefits.
- Boosted discharge efficiency by 30% in major construction projects. Reduced energy use by ¥2 million annually with smart ventilation. Enhanced dust control by 30% in Qinghai Salt Lake plant.

应 用 证 明

产品名称	储油洞库群施工通风优化设计及智慧运维关键技术		
应用单位	中国石油天然气管道工程有限公司		
应用成果起止时间	2024.01—至今		
通讯地址	河北省廊坊市广阳区和平路 146 号中国管道设计大厦	邮编	065000
联系电话	15100403484	联系人	王瑞卿
经济效益（万元）			
年度	2024 年		
新增产值（产量）	200 万		
新增利、税（纯收入）	--		
创收外汇、增收节支	100 万		

应用情况及社会效益

近年来，大连理工大学建设工程学院赵宇老师率领其团队利用其研发的储油洞库群施工通风优化设计及智慧运维关键技术，先后为我公司在国家石油储备五期LNJZ和GXQZ地下水封洞库项目的储油洞室施工通风中提供技术支持和服务，并将在未来进一步应用在本公司承担的各环控系统智慧运维平台的新建及改扩建工程中，解决了高浓度地下储油洞室内污染预测时效性差、精度低等问题，实现了上述场景环控系统综合排污效率提升 30%的目标，目前 LNJZ 和 GXQZ 两项目正在施工中，预估项目整体节省电费不低于 3000 余万元，取得了非常好的经济和社会效益。

应用法人单位公章：

2025 年 2 月 25 日

应 用 证 明

产品名称	高大空间典型污染物在线快速辨识及气溶胶传播风险预测平台		
应用单位	大连名达信息技术有限公司		
应用成果起止时间	2020.01-2023.10		
通讯地址	辽宁省大连市沙河口区南平街 33 号 6 单元 5 层 1 号	邮编	116000
联系电话	18640956156	联系人	马国峰
经济效益（万元）			
年度	2020-2023		
新增产值（产量）	200		
新增利、税（纯收入）			
创收外汇、增收节支	100		

应用情况及社会效益

近年来，大连理工大学建设工程学院赵宇老师率领其团队利用其研发的高大空间典型污染物在线快速辨识及气溶胶传播风险预测平台，先后为我公司在深圳水务集团污泥技改应急处理工程和中石油管道局西气东输天然气管线阀室环境安全模拟等项目中提供技术支持和服务，并将在未来进一步应用在本公司承担的各类环控系统智慧运维平台的新建及改扩建工程中，解决了高浓度封闭场所内污染预测时效性差、精度低等问题，实现了工业场景环控系统综合排污效率提升 15%的目标，保证了工程质量，取得了良好的经济和社会效率。

应用法人单位公章：

2023 年 11 月 9 日

应 用 证 明

产品名称	一种基于大数据学习技术的自动化智能风机管理系统等环控系统智慧运维相关技术		
应用单位	辽宁益安消防科技集团有限公司		
应用成果起止时间	2021.05-2023.10		
通讯地址	辽宁省大连市旅顺经济开发区顺乐街 730 号	邮编	116046
联系电话	0411-39368822	联系人	张喜胜
经济效益（万元）			
年度	2021-2023		
新增产值（产量）	300		
新增利、税（纯收入）			
创收外汇、增收节支	100		

应用情况及社会效益

近年来，大连理工大学建设工程学院赵宇老师率领其团队利用其研发的一种基于大数据学习技术的自动化智能风机管理系统等环控系统智慧运维相关技术，先后为我单位完成了新型智能风机系统产品开发及智慧运维平台的研发工作，成果应用在新建工程大连湾海底隧道通风环控智慧运维系统中，并将在未来进一步应用在本公司承担的各类消防、人防和通风环控新建及改扩建工程中，解决了长大隧道通风系统运行效率低的问题，实现了系统综合节能率不低于 20%的目标，保证了工程质量，取得了良好的经济和社会效率。

应用法人单位公章：

2023 年 11 月 9 日

项目参与证明

兹证明，大连理工大学建筑能源研究所赵天怡与赵宇的科研团队自 2021 年 5 月，作为项目骨干参与了"大连湾海底隧道和光明路延伸工程运维方案编制（合同编号：DLHS-01-ZX-87）"的技术咨询工作。运维方案的编制对象大连湾海底隧道工程主线全长约 5.1km、光明路延伸工程主线全长约 7km。

该科研团队负责本项目与机电设备系统相关的技术咨询工作，具体承担了大连湾海底隧道和光明路延伸工程的：①照明与通风系统的设计方案优化；②机电设施智慧运维方案的编制；③机电设施运维预算清单的计算。

以上工作覆盖的机电设备数量如下表所示。

分项	子分项	大连湾海底隧道	光明路延伸工程	七号路
供配电设施	变压器与稳压器	32	4	2
	配电柜与电源柜	129	66	2
	电机控制柜	12	48	2
	开关箱与电源箱	25	21	22
	蓄电池	91	29	2
照明设施	荧光灯	0	120	0
	LED 灯	10412	9316	1859
通风设施	风机	208	60	3
	风阀	517	100	0
消防与给排水设施	消火栓	314	118	54
	消防水泵结合器	20	16	0
	消防喷头	2264	1388	0
	火灾报警系统	297	1	0
	手动报警器	348	8	0
监控设施	交通监控摄像、无线通信、有线广播及程控电话系统	4	4	0
	可变情报板	4	4	0
	车道信号灯、安全标志灯、交通导向灯	1195	376	60
以上设备总计（台套）		27910		

大连湾海底隧道有限公司

（盖章）

年 月 日

大连理工大学
DALIAN UNIVERSITY OF TECHNOLOGY

Thank you

Assoc. Prof. Yu Zhao

2025. 04