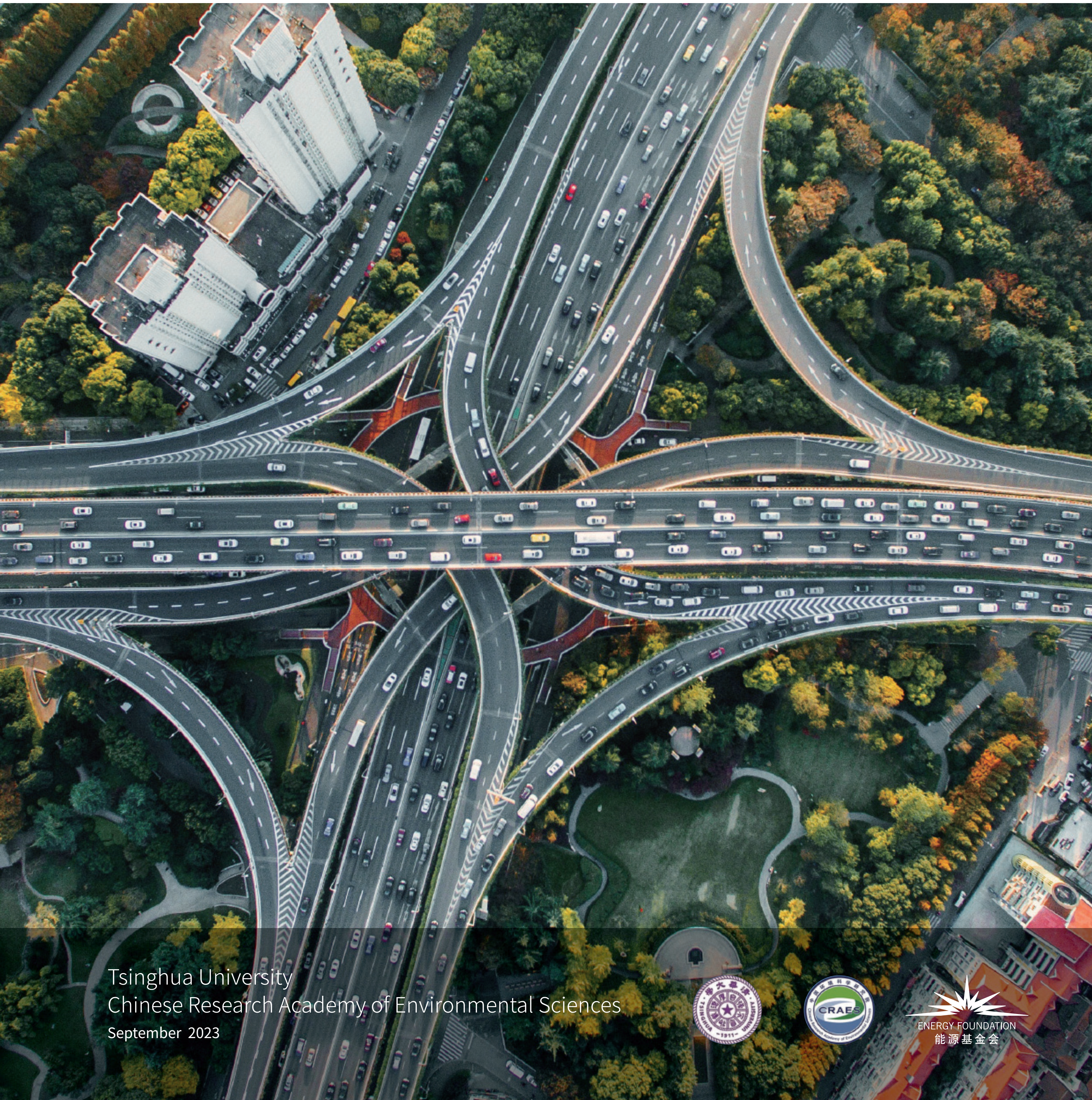
A Retrospective and Prospective Study on 20 Years' Mobile Source Emissions Control in Megacities of China



Tsinghua University
Chinese Research Academy of Environmental Sciences

September 2023

ENERGY FOUNDATION
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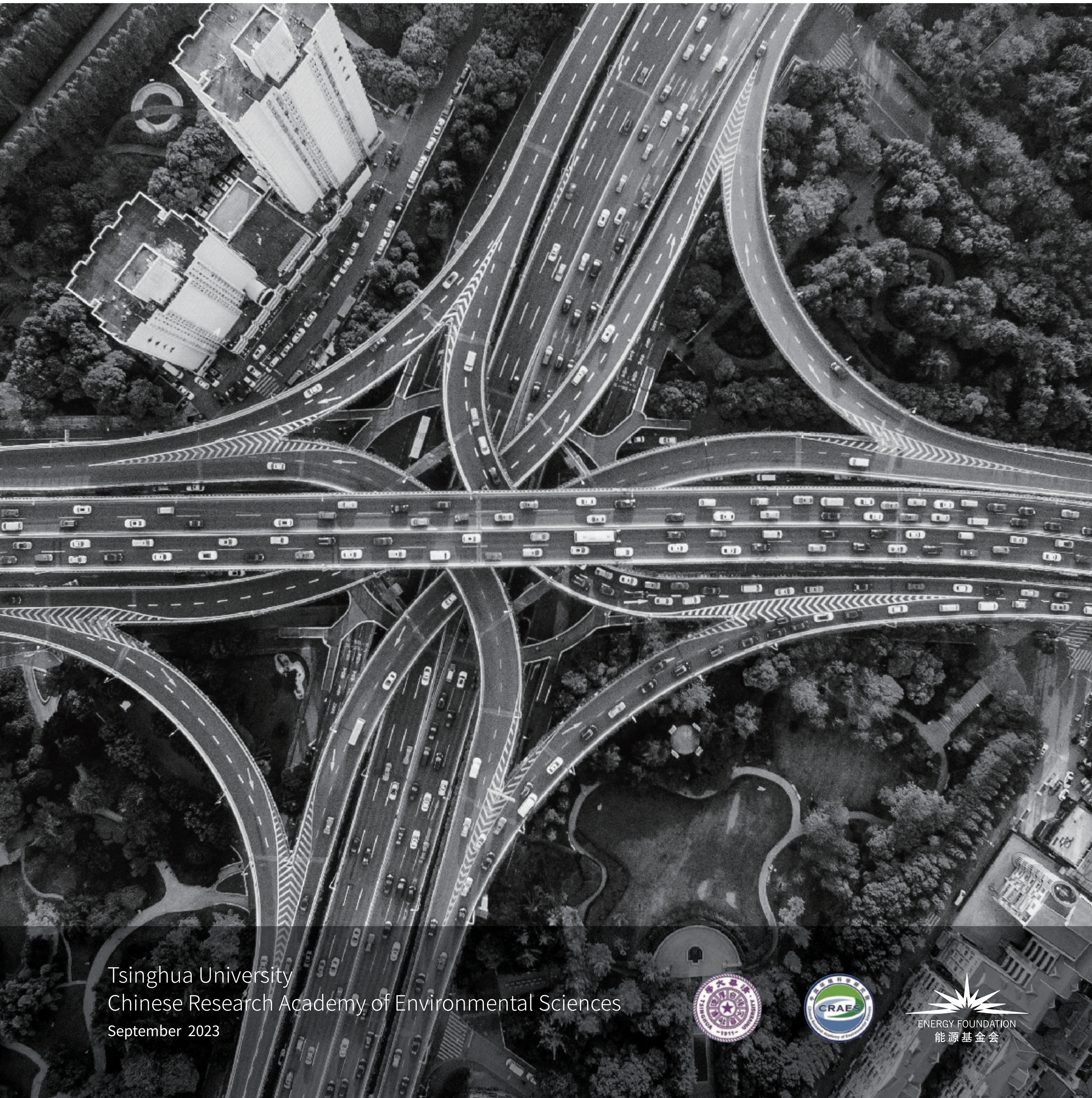

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Content

Abbreviations

ASM — Acceleration Simulation Mode

BEV — Battery Electric Vehicle

CO — Carbon Monoxide

CO_2 — Carbon Dioxide

DPF — Diesel Particulate Filter

GDP — Gross Domestic Product

GPS — Global Positioning System

HC — Hydrocarbon

HCHO — Formaldehyde

ICCT — International Council on Clean Transportation

ITS — Intelligent Transportation System

LEZ — Low Emission Zone

LPG — Liquefied Petroleum Gas

NG — Natural Gas

NMHC — Non-methane Hydrocarbon

NH_3 — Ammonia

NO_2 — Nitrogen Dioxide

NO_X — Nitrogen Oxides

O_3 — Ozone

OBD — On-Board Diagnostics

PAHs — Polycyclic Aromatic Hydrocarbons

PEMS — Portable Emission Measurement System

PHEV — Plug-in Hybrid Electric Vehicle

$PM_{2.5}$ — Fine Particulate Matter

PN — Particle Number

RFID — Radio Frequency Identification

SCR — Selective Catalytic Reduction

VOCs — Volatile Organic Compounds

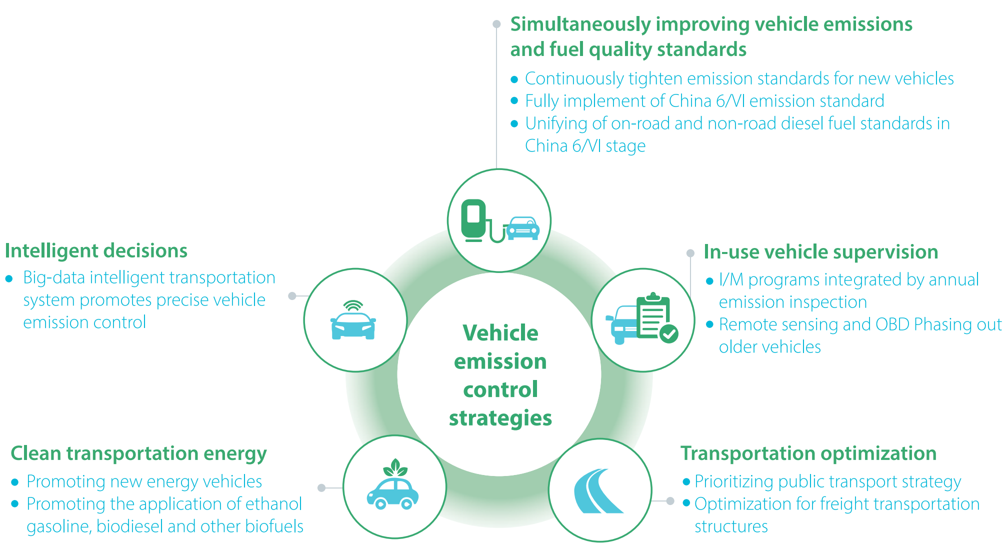
Executive Summary

Executive Summary

Due to socioeconomic development and rapid urbanization, the automotive market in China has experienced exponential growth over the past three decades. This remarkable surge in motorization serves as a testament to China's thriving economy. Since 2009, China has held the position as the largest automotive market globally and in 2013, it became the first country to exceed annual sales of 20 million new vehicles. In terms of total vehicle population, China overtook the United States of America in 2021, solidifying its leading position. While rapid motorization contributes to industrial and social development by enhancing travel convenience, it also presents substantial challenges concerning air quality, public health, energy security, and climate change.

As early as the mid-1990s, China became aware of vehicle-related air pollution issues and started learning effective control measures from developed countries. In 2000, China implemented the China 1 emission standards, a milestone that marked the beginning of comprehensive control of vehicle emissions at the national level. During the past 20 years, China has formulated and implemented a series of control policies and measures to address this issue. These include continuous upgrades to vehicle emission standards, improvements in fuel quality, enhanced controls on in-use vehicle emissions, promotion of new energy vehicles (NEVs), and optimization of transport planning and management. As a result, the integrated "vehicle-fuel-traffic" control system has been developed and progressively enhanced (Fig. 1). Currently, China has fully implemented the China 6/VI standards for vehicle emissions and fuel quality. Additionally, advanced technologies for monitoring real-world emissions have been piloted, and efforts to optimize transportation modes and energy structures have been initiated. Notably, China has emerged as a global leader in promoting NEVs. These two decades of concerted efforts have significantly reduced the gap between vehicle emission control in China and that in most developed countries.

Fig.1. Integrated "vehicle-fuel-traffic" emission control system in China



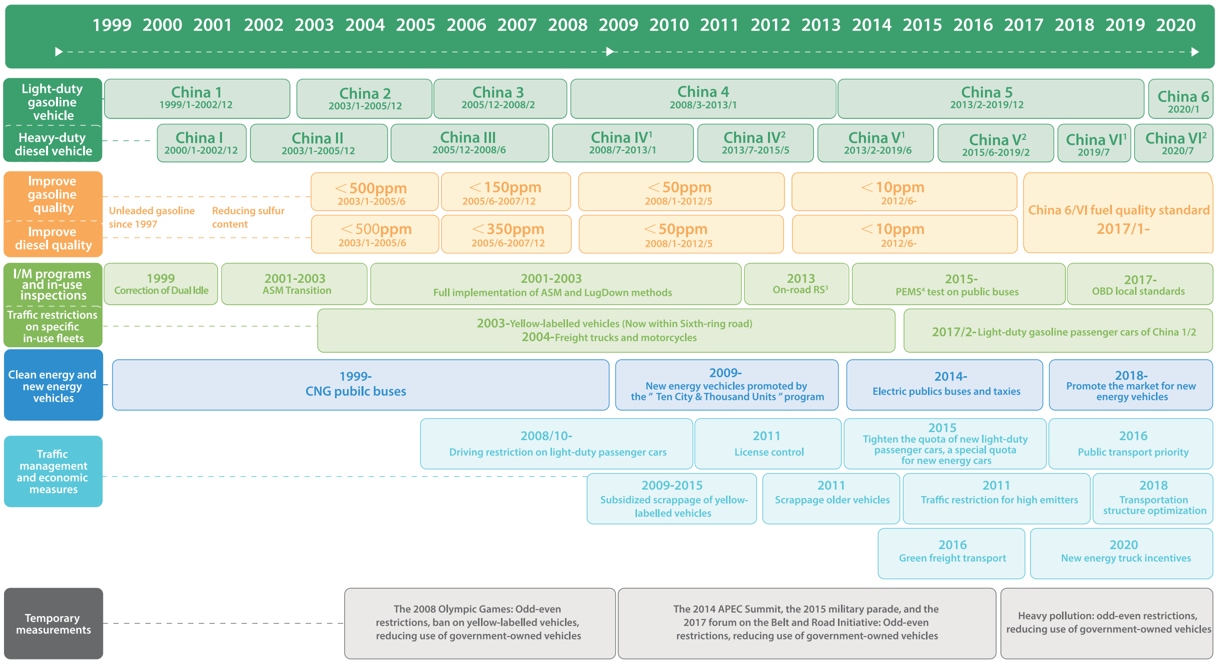
In China, megacities have played a crucial role in showcasing new measures for controlling vehicle emissions, resulting in progress on a national scale. Megacities, being hubs of vehicle concentration and frequent usage (Fig. 2), constantly strive to regulate vehicle emissions and enhance air quality. The practical experiences gained from these megacities can serve as valuable support for implementing effective vehicle emission control policies at the national level. For example, over the past two decades, Beijing has pioneered the development of the integrated "vehicle-fuel-traffic" control system. This included the prohibition of leaded gasoline in 1997 and the implementation of the China 1 emission standard for light-duty gasoline vehicles (LDGVs) in January 1999. These measures were later adopted by the central government after one or two years (Fig. 4). In Shanghai, notable progress has been made in promoting public transport systems and diversifying transport energy. Shenzhen has achieved a significant milestone by being the first city in the world to fully electrify its public bus and taxi fleets, leveraging its well-developed local NEV industry. Lastly, Chengdu has developed a smart, data-driven system for managing vehicle emissions by utilizing extensive traffic data collected from intelligent transport systems. All these cities have implemented various control measures and practices tailored to their unique characteristics (Fig. 3). Despite significant increases in the number of vehicles, they have effectively managed to decouple urban transportation development and the trend of on-road emissions (Fig. 5, for the Beijing case). These studies have not only accelerated the improvement of air quality in megacities but also provided valuable insights for other cities to pursue green and low-carbon development paths for their transportation systems.

Fig. 2. Economic and demographic conditions of Beijing, Shanghai, Shenzhen, and Chengdu in 2020

	Area (km²)	Population (million)	GDP per capita (k CNY)	Vehicle population (million vehicles)
Beijing	16,410	21.9 Annually 2.4% ↑	165 Annually 10.0% ↑	6.57 Annually 9.1% ↑
Shanghai	6,341	24.9 Annually 2.2% ↑	157 Annually 8.6% ↑	4.69 Annually 11.5% ↑
Shenzhen	1,997	17.6 Annually 4.7%	158 Annually 8.1% ↑	3.59 Annually 12.5% ↑
Chengdu	14,335	20.9 Annually 3.2% ↑	85 Annually 11.1% ↑	6.03 Annually 11.1% ↑

Fig. 3. Featured municipal-level control policies in four representative megacities in China

Beijing: A pioneer city for vehicle-fuel-traffic integrated control

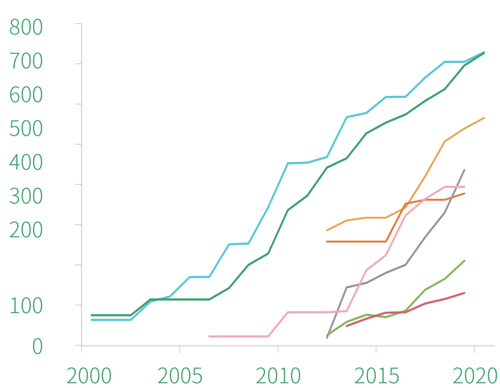


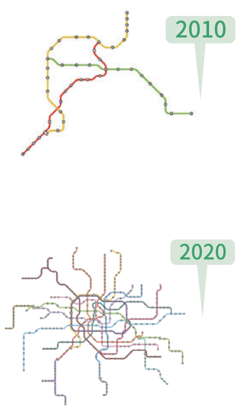
[1] Only implemented for public fleets; [2] for freight trucks and long-distance coaches: [3] remote sensing test; [4] portable emission measurement system

Shanghai : Promoting public transport systems and diversifying transport energy

▼ Subway development

▼ Operating mileage of rail transit (km)





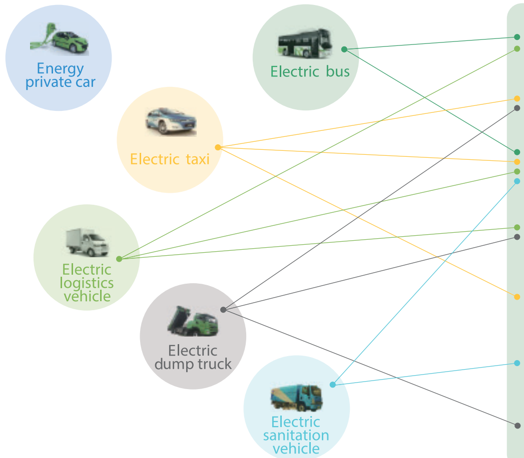
▼ Application of biodiesel

Shenzhen : Promoting new energy vehicles and establishing comprehensive industrial layout

Common measures | Special measures

1. Policy support
2. Fiscal purchase subsidy
3. Promoting the construction of public charging infrastructures

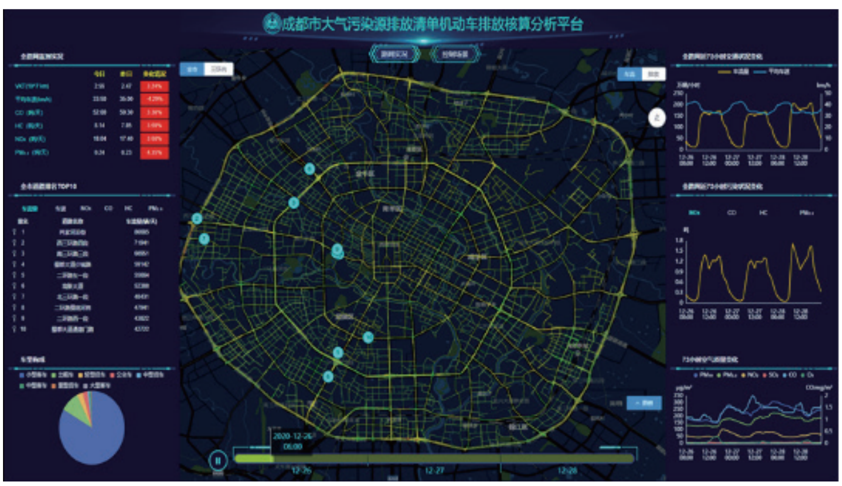
❶ Bus charging station ❷ Car charging station



1. Providing fiscal subsidy for operation
2. Providing incentives and subsidy for extra emission reduction
3. Building supporting charging infrastructures
4. Exempt from traffic restrictions
5. Providing indicator incentives for the right of operation
6. Raising the section price of procurement service
7. Compiling and releasing norms and standards in term of NEVs

Chengdu: Big-data intelligent transportation system promotes precise emission control

Intelligent vehicle emissions mapping and management system | ITS facilities



Hourly, link-based

Fig. 4. Growth trend in vehicle population and key moments regarding vehicle emission control in Beijing during 2000-2020

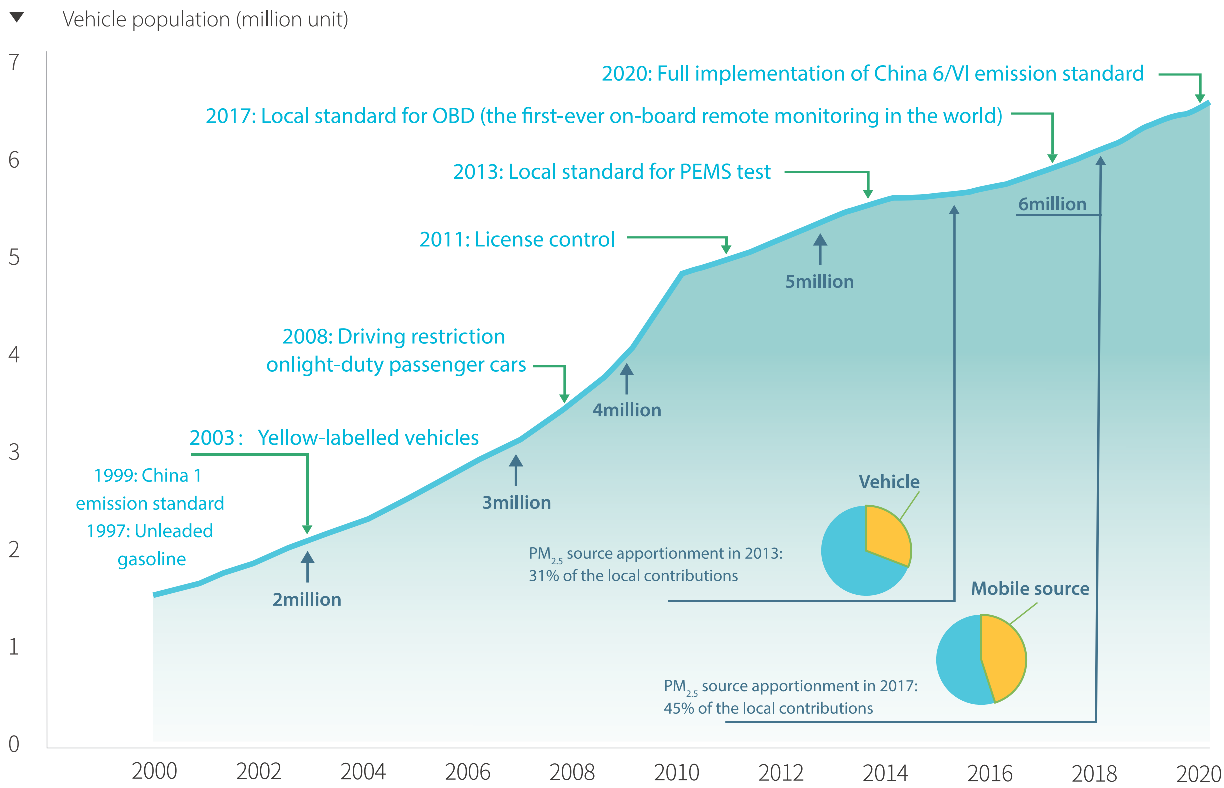
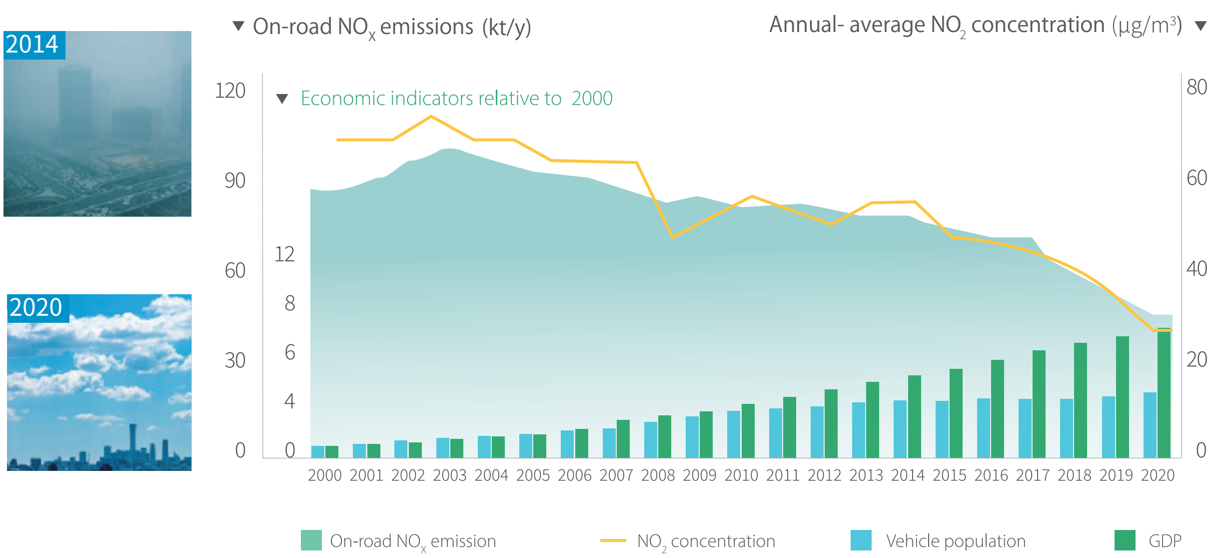


Fig. 5. Decoupling on-road emissions resulting from rapid growth of vehicle ownership in Beijing during 2000–2020



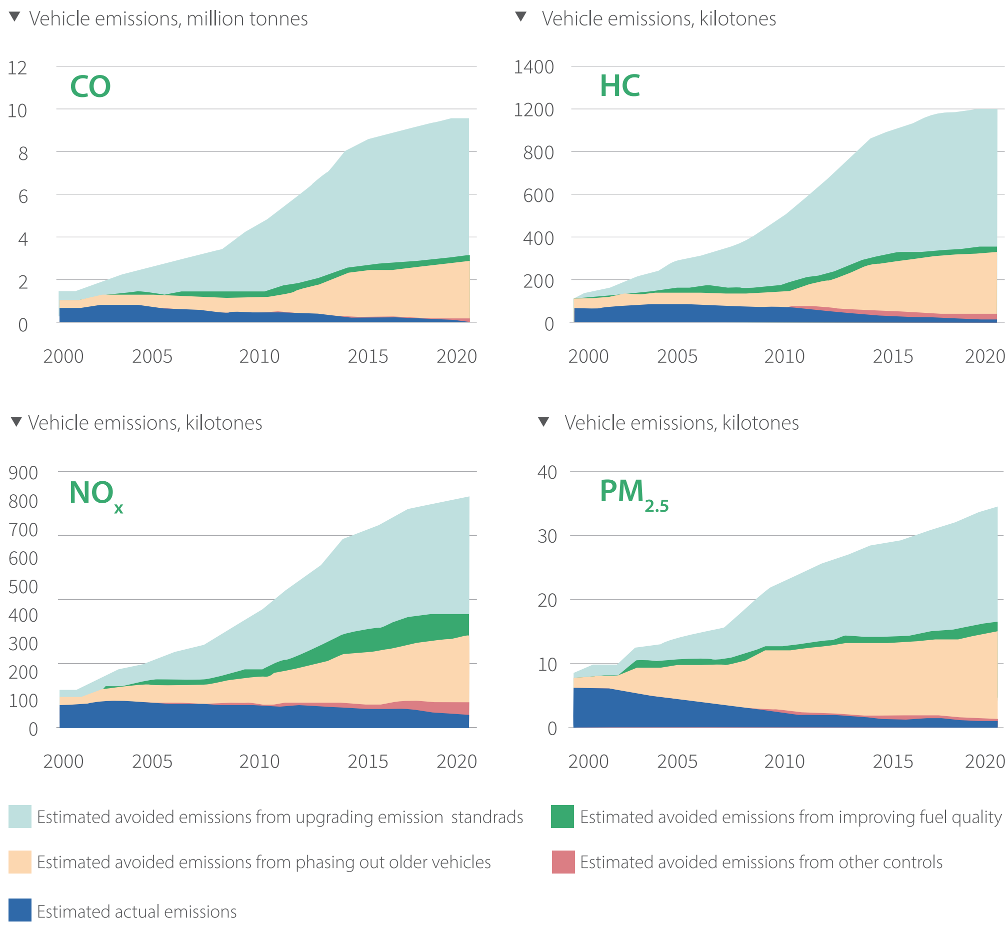
The significant observations from vehicle emission management in Beijing, Shanghai, Shenzhen, and Chengdu along with the progress made at the national level over the past two decades are summarized below.

1. Simultaneous enhancement of vehicle emissions and fuel quality standards

Enhancements in emission standards have played a central role in reducing on-road emissions in China over the last 20 years. Notably, Beijing has continuously tightened its emission standards for new vehicles. In January 1999, Beijing became the first Chinese city to implement the China 1 emission standards (equivalent to Euro 1) for LDGVs and since then it has consistently implemented more stringent vehicle emission standards compared to other cities in China. This has established Beijing as the national leader in vehicle emission control. In 2020, Beijing adopted the China 6/VI emission standards, which are among the most rigorous regulations worldwide, and these standards were subsequently adopted nationwide. The continuous enhancement of emission standards not only promotes the advancement of the automotive industry but also safeguards the environment.

Moreover, Beijing's success highlights the importance of integrating vehicle emissions and fuel quality standards to maximize the emission reduction benefits of existing vehicle emission standards. In the late 1990s, Beijing began improving its fuel quality standards by prohibiting leaded gasoline (1997) and high sulfur content fuels (2012). When nationwide implementation of emission standards faced delays due to the lack of high-quality fuels (e.g., low sulfur content diesel fuels), Beijing took the lead in implementing fuel standards in China's 2/II to 5/V stages, ensuring synchronized implementation with emission standards. The timely upgrading of fuel quality standards in Beijing served as a model for the harmonized improvement of vehicle emissions and fuel quality in China. Specifically, Beijing's experience facilitated the nationwide implementation of China 5/V emission and fuel quality standards while unifying the on-road and non-road diesel fuel standards under China 6/VI. These synchronous enhancements in emission and fuel quality standards have effectively reduced vehicle emissions in Beijing. These improvements are responsible for 74%, 73%, 66%, and 55% of the total vehicle emission reductions in carbon monoxide (CO), hydrocarbon (HC), nitrogen oxides (NO_X), and fine particulate matter ($PM_{2.5}$) emissions from 2000 to 2020 (Fig. 6).

Fig. 6. Assessment of vehicle emission reduction in Beijing during 2000-2020



2. Integration of multiple advanced technologies for the emission monitoring of in-use vehicles

Supervising in-use vehicles has always been a crucial yet challenging aspect of vehicle emission control. To strengthen compliance with the real-world emission standards for existing vehicle fleets, China has implemented several new regulations and standards that combine multiple advanced technologies with in-use inspection and compliance programs.

Taking Beijing as a representative example, a comprehensive inspection system that integrates multiple monitoring techniques for in-use vehicles has been developed, and a regular supervision mechanism has been established after 20 years of practice. This system has strengthened the inspection and maintenance (I/M) program which plays a pivotal role in controlling emissions from in-use vehicles. Over the past two decades, Beijing has consistently adopted advanced inspection technologies to monitor emissions from in-use vehicles.

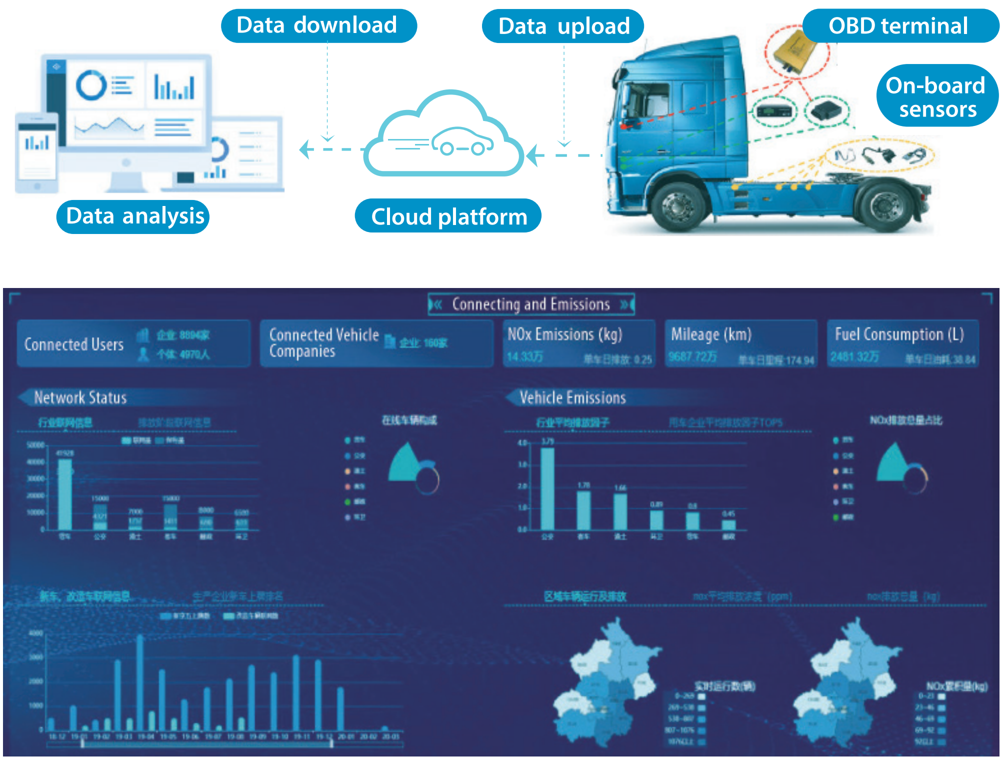
In 1999, Beijing revised the two-speed idle test method and the standard limits for new vehicles manufactured after the implementation of the China 1 standards. The more stringent acceleration simulation mode (ASM) method was fully implemented in 2003, with subsequent updates that further tightened the emission limits. For in-use diesel vehicles, Beijing introduced a lug-down test in 2003 further tightening the smoke emission limits. These advanced methods along with stringent emission limits, have significantly improved the ability to accurately identify high emitters.

In recent years, Beijing has embraced more real-world methods to improve its supervision capabilities and facilitate the development of comprehensive supervision platforms. Various advanced on-road monitoring technologies, including roadside remote sensing, portable emission measurement systems (PEMS), and remote on-board diagnostics (OBD), have been applied in Beijing.

Among the pollution challenges, the excessive real-world NO_X emissions from heavy-duty diesel vehicles (HDDVs) is the most prominent issue for policymakers. Beijing became the world's first city to implement remote OBD monitoring to enhance the compliance of in-use HDDVs. Local standards and regulations were introduced requiring original equipment manufacturers to participate in the installation of OBD devices for new and in-use HDDVs. These local experiences resulted in the assimilation of remote OBD monitoring protocols in the China VI emission limits. Currently, an online platform with over 100,000 in-use HDDVs has been preliminarily established (Fig. 7).

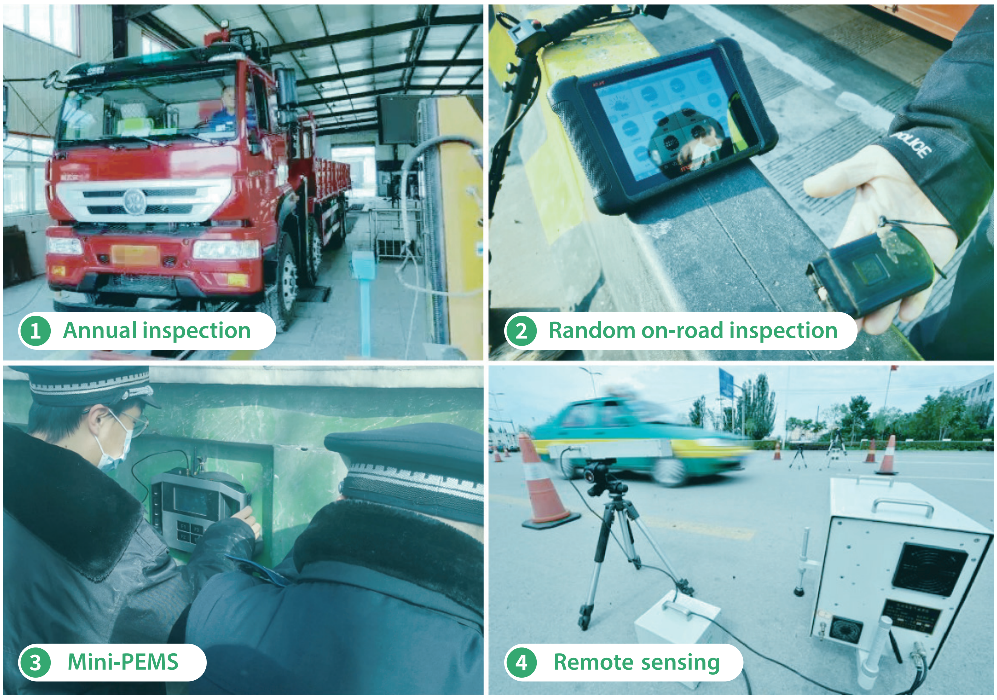
The powerful and efficient remote OBD monitoring has resulted in significant reduction in NO_x emissions from HDDVs in Beijing. The average NO_X emission factor for Beijing V HDDVs equipped with OBD monitoring is 50-70% lower than that of regular China V HDDVs without OBD monitoring, leading to effective mitigation of $PM_{2.5}$ and nitrogen dioxide (NO_2) pollution. Notably, in Beijing, the estimated NO_X emissions from diesel trucks in 2020 decreased by 43%, compared to 2017, surpassing California's reduction rate over the same three year period (~37%). Consequently, the annual average ambient NO_2 concentration in Beijing decreased by 37% during these three years, meeting the national ambient air quality standard for the first time in 2019.

Fig. 7. Beijing's remote on-board diagnostics (OBD) monitoring platform for heavy-duty diesel vehicles (HDDVs)



To summarize the experience gained from in-use vehicle supervision, China has established inspection and maintenance (I/M) programs, including annual emission inspection, random emission inspection, PEMS, and remote sensing (Fig. 8). The installation of on-board monitoring hardware is mandatory for the China VI-a standards for HDDVs, and data submission is required to adhere to the China VI-b standards, emphasizing the future importance of OBD monitoring.

Fig. 8. Annual inspection and random on-road emission inspection of in-use vehicles



3. Implementation of "Prioritizing Public Transport" strategy and optimization of freight transportation structure

Reshaping public transport systems and encouraging sustainable green travel modes are fundamental measures for cities to develop green and low-carbon transport systems amidst urbanization. Cities, such as Shanghai and Beijing attach great importance to optimizing public transportation systems and non-motorized transport modes to cope with the increasing pressure of transportation demand while transitioning to efficient, green, and low-carbon transportation.

Shanghai was the first city in China to adopt the "Prioritizing Public Transport" strategy as a key component of urban development. In conjunction with urban and traffic planning, Shanghai has issued a series of policies to develop subways, optimize bus routes, and encourage public transport and non-motorized transport modes. Alongside license quota restrictions, the urban transport structure in Shanghai has undergone significant optimization, effectively alleviating traffic-related environmental problems (Fig. 9). In 2020, the proportion of public transport in Shanghai increased to 47% of trips, and the length of Shanghai's subway lines exceeded 700 km, representing a tenfold increase compared to 2000. The total length of bus-only lanes reached 500 km, and the central area achieved full coverage of bus stops within a 300 m radius. Notably, in 2020, the vehicle ownership density in Shanghai was capped at approximately 180 vehicles per 1000 people, the lowest among other domestic megacities with similar gross domestic product (GDP) per capita. As a result, vehicular NO_X and volatile organic compound (VOC) emissions in the region have continuously decreased. The NO_2 concentration in the urban area decreased by 18% from 2015 to 2020, with significant reductions observed in high concentration areas (Fig. 10). Over the past 20 years, Shanghai has successfully pioneered a green and low-carbon transportation development path that combines a public transportation priority strategy with comprehensive control of traditional vehicle emissions.

Fig. 9. Changes in travel mode and development of subways in Shanghai

a. Travel volume and travel mode **b. Development of subways**

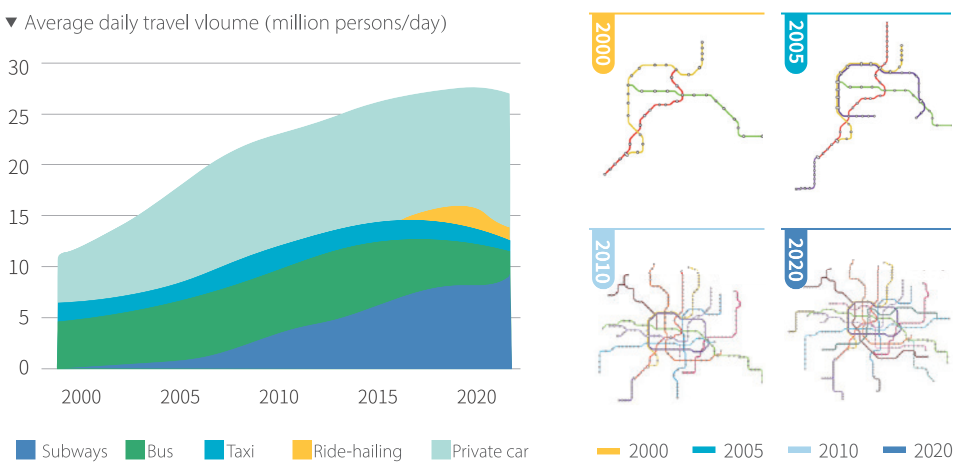
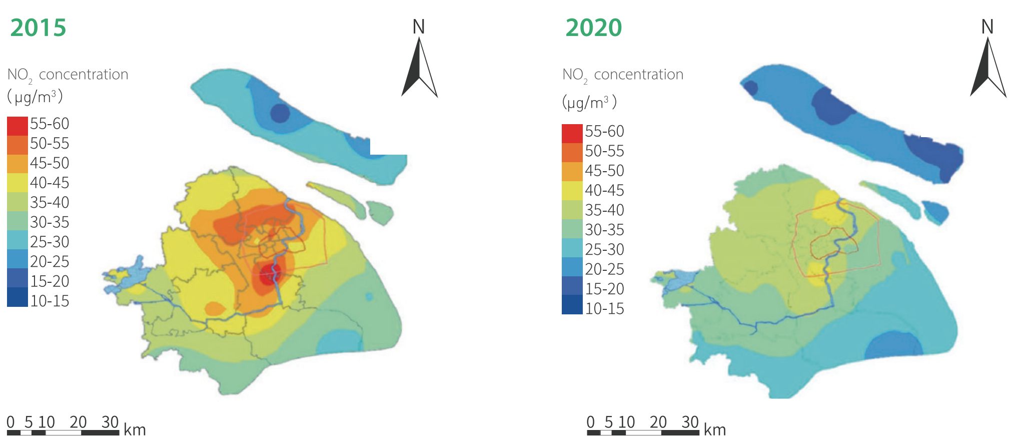


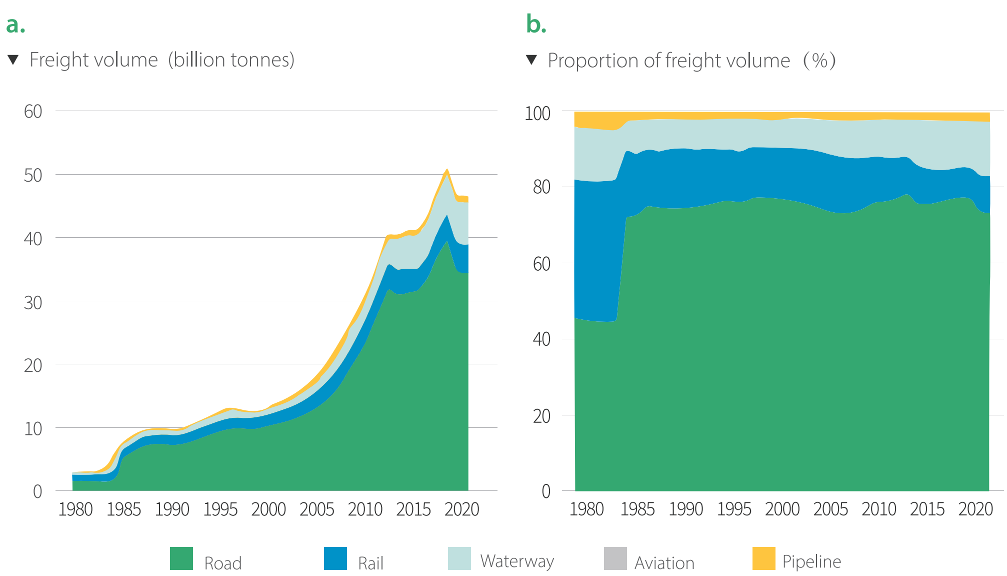
Fig.10. Spatial distribution of ambient NO_2 concentrations in Shanghai in 2015 and 2020



Over the past two decades, China has witnessed a rapid increase in freight transportation volume, currently ranking first globally. On-road trucks have dominated the freight transportation volume, while the proportion of railway transportation has continued to decrease. Generally, waterways and railways exhibit significantly lower energy consumption and pollutant emissions per unit of freight turnover compared to on-road trucks. Therefore, increasing the proportion of railway and waterway systems through modal shift can effectively reduce air pollutants and CO_2 emissions. Optimizing the transportation structure is of great significance in achieving vehicle emission mitigation, especially for heavy-duty trucks, and supply-side structural reforms.

The Three-Year Action Plan for Winning the Blue-Sky Defense War and the Three-Year Action Plan for Promoting Transportation Structure Adjustment have emphasized the crucial role of adjusting the transportation structure in controlling diesel truck pollution. To promote the "road to rail" and "road to water" transitions for bulk cargo transportation, the Chinese government has implemented economic measures and support policies for infrastructure construction. Since the implementation of these action plans, the predominant role of road transportation has started to shift. From 2017 to 2020, the share of railway cargo transportation in China experienced a rebound, with an average annual growth rate of 7%, while the share of road cargo transportation decreased from 78% in 2017 to 74% in 2020. Notably, the transportation structure for bulk goods in coastal ports in the Bohai Rim and Yangtze River Delta regions has undergone significant optimization. However, compared to the historical proportion of railway freight (over 30% in 1980), the adjustment of the transportation structure is still in its early stages (Fig. 11).

Fig. 11. Trends in freight volume and modal proportion in China during 1980–2020



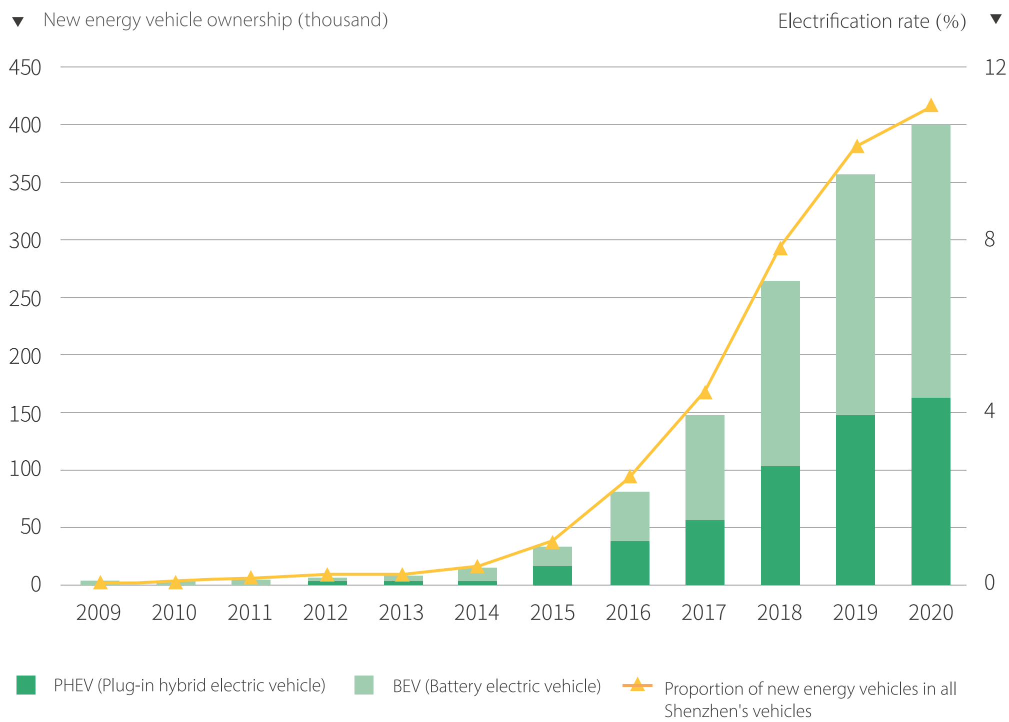
4. Comprehensive development of NEVs and promotion of zero-emission vehicles

The promotion of NEVs offers significant benefits as they have the ability to synergistically reduce pollutants and carbon emissions. To align with global sustainability goals and mitigate climate change, it is critical for China to develop a clean and efficient modern energy system and achieve a green and low-carbon industrial transformation. This is also a key measure for China to meet its long-term objective of clean air and carbon neutrality. China pioneered the "Ten Cities, Thousand New Energy Vehicles" demonstration project in 2009, which involved 1,000 NEVs in 10 cities. Since then, China has launched a series of measures to promote NEVs and currently holds the title of the world's largest producer and seller of NEVs. These measures include purchase subsidies, tax exemptions, infrastructure construction, and the promotion of dual-credits for corporate average fuel consumption-sales of new energy vehicles (CAFC-NEV). By the end of 2020, the NEV stock in China reached 4.92 million, accounting for over 40% of the global NEV total and exhibiting sustained rapid growth.

Shenzhen is one of the pioneer cities in China for significantly promoting the use of NEVs and has been awarded the title of the "Capital of Electric Vehicles in the World" for six consecutive years. Shenzhen has successfully promoted approximately 400,000 NEVs, which accounts for 11% of its total vehicle stock. Not only does Shenzhen have the highest electrification rate among all Chinese megacities, Shenzhen is also the first city in the world to fully electrify its bus and taxi fleets, and it had the highest number of electric trucks globally from 2015 to 2020.

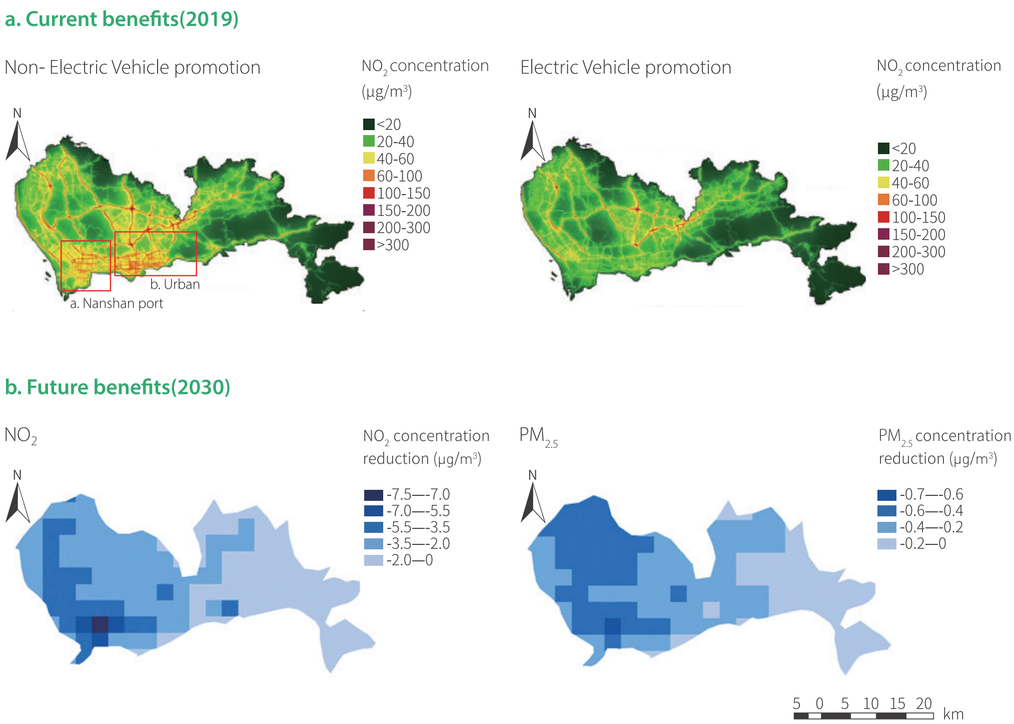
The rapid development of electric vehicles in Shenzhen can be attributed to the comprehensive construction of a supportive system and the establishment of a sound NEV industry layout. Over the past 10 years, the city has issued more than 30 standards and administrative rules directly related to NEVs. Additionally, a comprehensive support system, including development planning, standard specifications, financial subsidies, and infrastructure construction, has been established. For example, Shenzhen has introduced diverse subsidies and incentive measures that cover different aspects of NEVs, such as purchase, usage, infrastructure, and battery recycling. Furthermore, fiscal incentives have played a significant role in promoting NEV development in the city. Notably, Shenzhen places great importance on the local landscape and ecosystem of the NEV industry. At present, Shenzhen has more than 2,000 NEV-related enterprises making it one of the cities with the highest density of NEV enterprises in the world.

Fig. 12. Growth in the total number of new energy vehicles (NEVs) in Shenzhen during 2009–2020



The rapid development of NEVs in Shenzhen has become a crucial element in achieving a local clean-air action plan known as "Shenzhen Blue". Since 2014, ambient NO_2 concentrations in Shenzhen have significantly improved, with 35% of the improvement attributed to fleet electrification (Fig. 13a). Further large-scale promotion of NEVs will continue to bring substantial improvements in air quality, such as coordinated control of $PM_{2.5}$ and ozone (O_3) pollution (Fig. 13b), along with associated health benefits. Moreover, NEVs will make significant contributions to reducing greenhouse gas emissions from on-road traffic throughout their life cycle.

Fig. 13. Air quality improvements in Shenzhen resulting from fleet electrification



5. Diversification of transportation energy and application of biofuel

Biofuels play a significant role in achieving diversified, clean, and low-carbon transportation energy in China. Over the past 20 years, China has actively promoted pilot applications of biofuels for vehicles. In recent years, ethanol gasoline has been consistently promoted to optimize the energy structure, improve the ecological environment, reduce CO_2 emissions, and address surplus aged grains. In 2017, 15 central ministries, including the National Development and Reform Commission, issued documents to promote ethanol gasoline and identified the overall structure of the biofuel production industry. Currently, E10 ethanol gasoline (a blend of 10% bioethanol and 90% gasoline) is sold in 15 provinces in China to varying extents (Fig. 14), with approximately 3 million tonnes of bioethanol supplied.

Fig. 14. Promotion of E10 ethanol gasoline in China

To address food safety concerns arising from the reuse of waste cooking oil, or "*gutter oil*", Shanghai has established a closed-loop management system for the entire waste cooking oil treatment industry. The system covers various aspects such as the collection, transportation, storage, disposal, and application of gutter oil (Fig. 15). Additionally, Shanghai has implemented the widespread use of B5 (a blend of 5% biodiesel and 95% diesel) and B10 biodiesel in buses and heavy-duty vehicles (HDVs). The amount of waste cooking oil collected in Shanghai has increased to over 200 tonnes per day, which can be converted into 50,000 tonnes of B100 biodiesel annually, replacing approximately 1% of diesel consumption in the transportation sector. These measures not only contribute to emission reduction and energy conservation but also provide valuable insights for the diversification of transportation energy in cities.

It is important to note that the scale of biofuel promotion in China lags behind that of countries like Brazil and the United States of America (USA). In 2020, bioethanol production reached 41.6 million tonnes in the USA and 24.3 million tonnes in Brazil, while biodiesel production in the European Union (EU) amounted to 13.6 million tonnes (Fig. 16). Therefore, considering China's commitment to reaching its CO_2 emission peak by 2030 and achieve carbon neutrality by 2060, more efforts are needed to promote research and development of biofuels in China.

Fig. 15. Illustration of the closed-loop governance model applied in Shanghai for the complete industrial chain of "gutter oil" to biodiesel

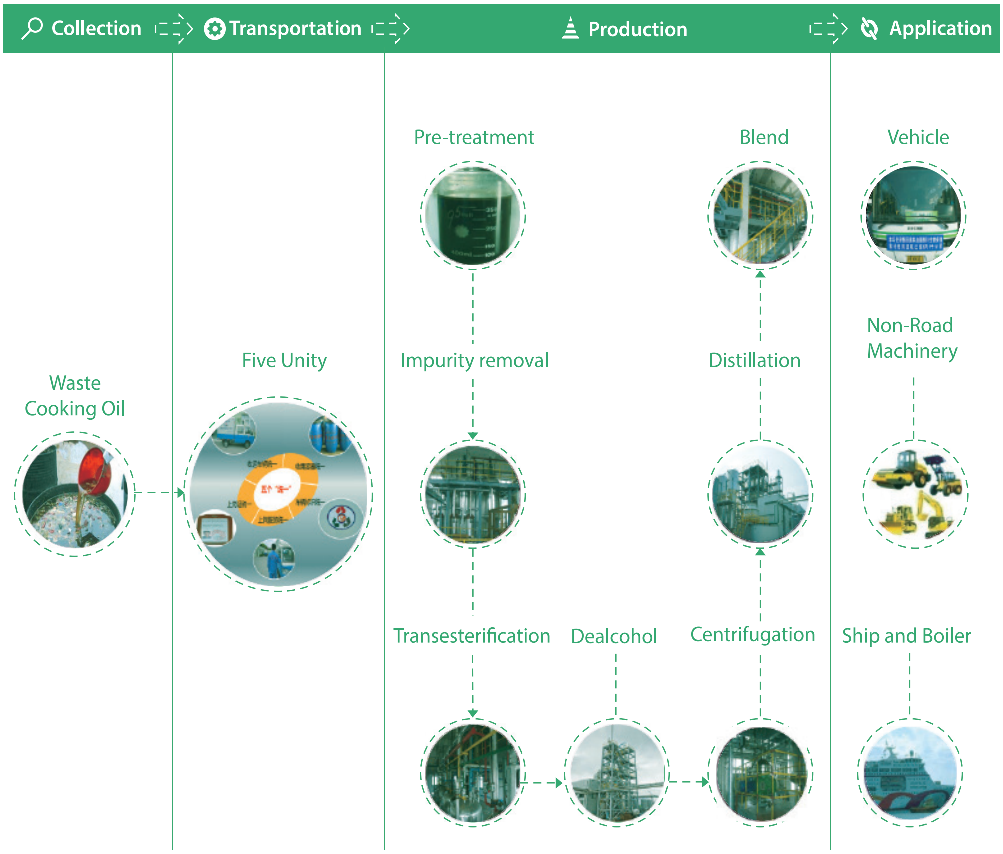
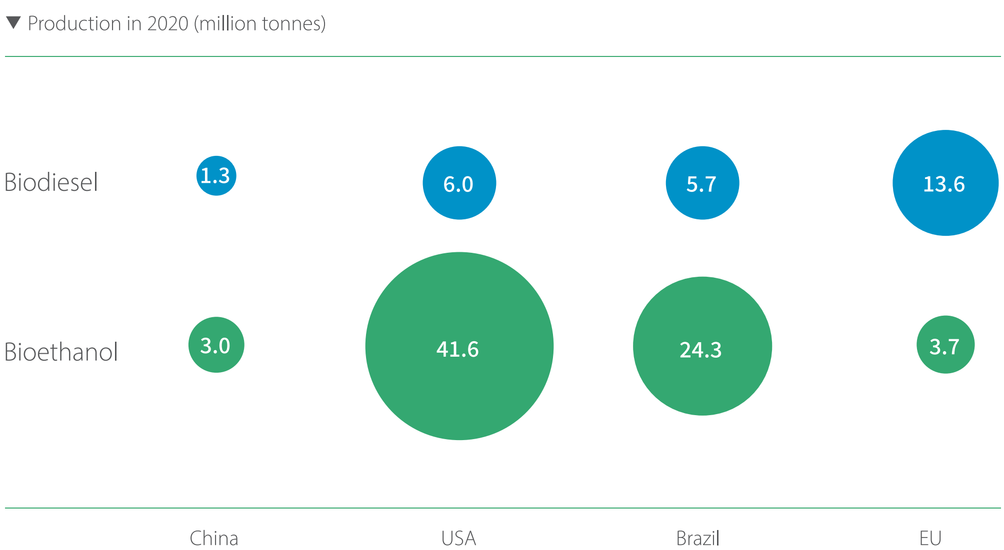


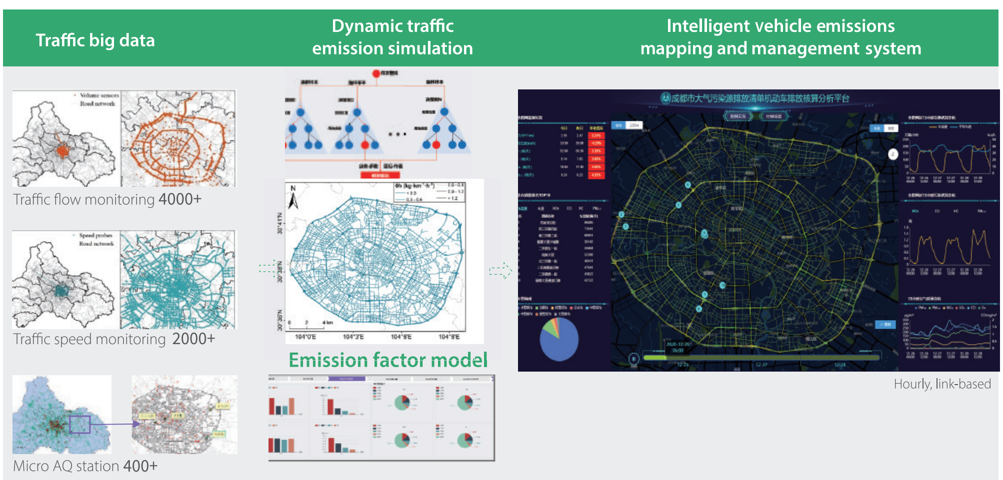
Fig. 16. Comparison of biofuel production in China, Brazil, the United States of America (USA) and the European Union (EU)



6. Big data intelligent transportation system to promote smart management of vehicle emissions

Intelligent transportation technology and the utilization of traffic big data can be effective strategies for intelligent traffic emission control. Rather than implementing license control measures to cap the growth of the total vehicle population, Chengdu, like other megacities, focusses on addressing traffic and environmental issues through data-driven intelligent technologies. In recent years, Chengdu has made significant efforts to develop and utilize Intelligent Transportation Systems (ITS). The city has established a monitoring network with a high density of traffic detectors (approximately 4,000 detectors within the urban area as of 2020) that transmit real-time traffic volume and fleet composition data. Integrated with a machine learning (ML) based traffic flow simulation method, Chengdu has developed a dynamic vehicle emission mapping and management system (Fig. 17). The latest version (V4.0, released in 2021) of this comprehensive decision-making system enables fast, accurate and high-resolution vehicle emission simulations for the entire city. For example, the system can effectively demonstrate link-level traffic flow and vehicle emissions continuously for 72 hours. The platform also allows for simulating the benefits of vehicle emission control in both short- and long-term scenarios, thereby improving the timeliness, accuracy, and intelligence of traffic emission supervision. The platform has been successfully utilized for dynamically tracking traffic and emission changes during the COVID-19 pandemic and evaluating the low-emission zone (LEZ) policy to ensure optimal traffic control during major events, such as the Chengdu World Police and Fire Games. It has provided significant technical support for fast and precise decision-making regarding vehicle emission control in Chengdu (Fig. 18).

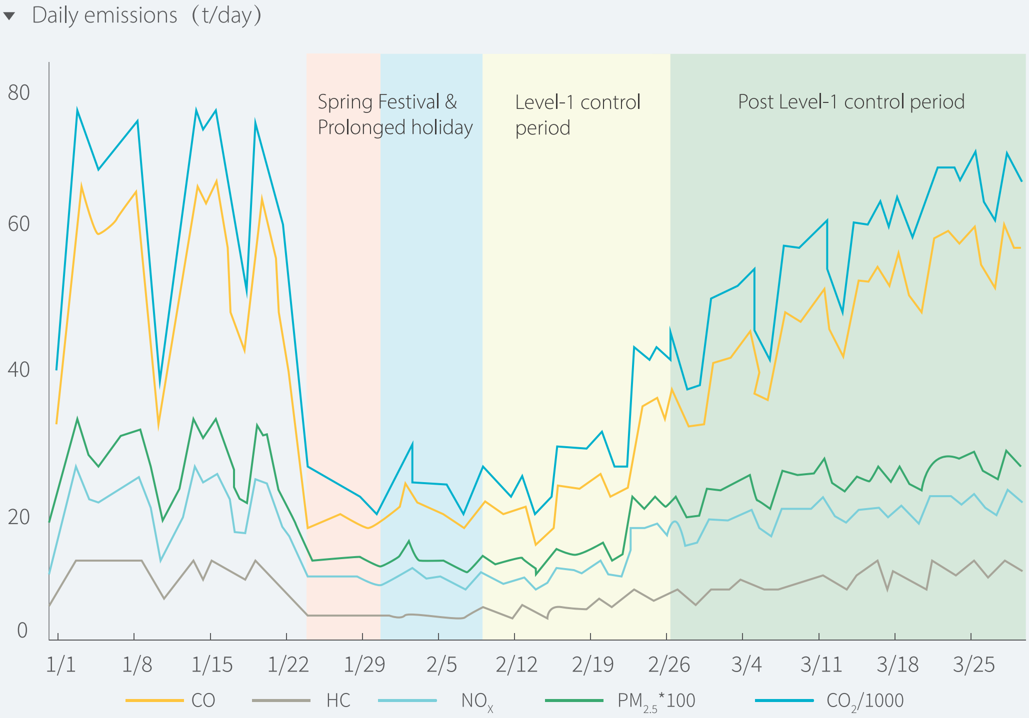
Fig. 17. On-road vehicle emissions mapping and management system of Chengdu based on Intelligent Transportation Systems (ITS) big data



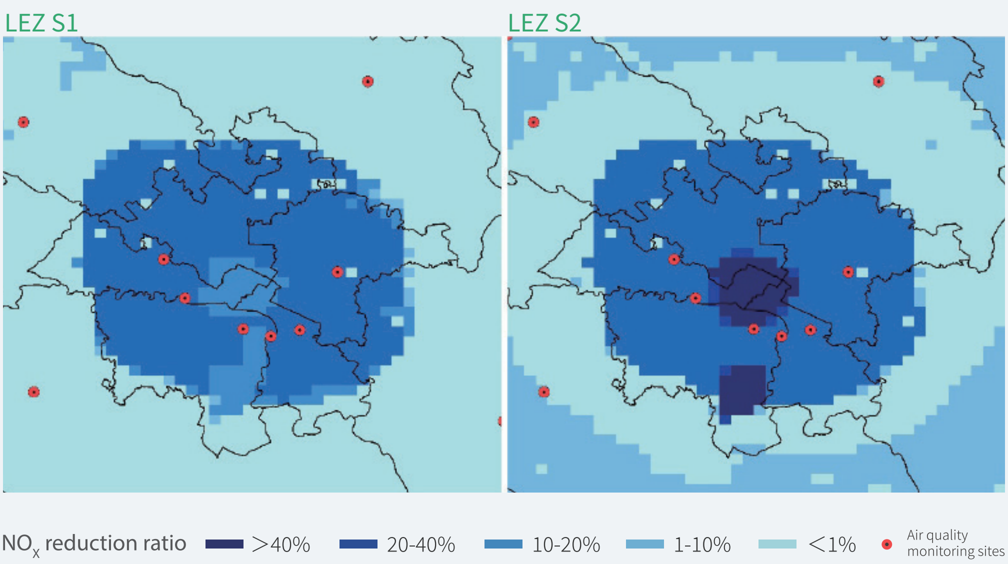
Assessments of the feasibility and expected effects of the LEZ policy indicate that its implementation in Chengdu can significantly reduce traffic intensity and vehicle emissions, leading to improved air quality in the city (Fig. 18b). In addition, the LEZ policy can be integrated with NEV promotion and transportation structure adjustments enhancing its role as a "green and low-carbon demonstration zone" that mitigates air pollution and CO_2 emissions. This conceptual leap could become an important strategy for developing green and low-carbon transportation systems in large cities. However, it is crucial to note that the successful implementation of the LEZ policy requires adequate legal support and supportive infrastructure. Therefore, careful consideration of all stakeholders and their concerns is necessary before implementation. Moreover, dynamic tracking and thorough evaluation is necessary before and during the policy's implementation. Importantly, the experience gained from applying big data ITS analytics can assist cities in achieving smart vehicle emission management and provide innovative solutions to other cities facing similar challenges due to rapid motorization.

Fig. 18. Implications of the on-road vehicle emissions mapping and management system applied in Chengdu.

a. Dynamic tracking of vehicle emission changes during the COVID-19 pandemic



b. Assessment of emission reduction resulting from the implementation of low-emission zone (LEZ) policies



Outlook

Although China has made tremendous progress and achievements in vehicle emission control, there is still a long way to go. With the projected vehicle stock reaching 400-500 million by 2030 the construction of a sustainable, clean, and low-carbon transportation system becomes a crucial task in the future development of China's transportation sector.

01 Deep emission abatement is critical for improving air quality and addressing climate change synergistically

Deep emission abatement for mobile sources is a major focus for reducing $PM_{2.5}$ and O_3 concentrations in China's megacities. Implementing scientifically based and precise vehicle emission control measures is a critical task to improve the air quality in China by 2035, aligning with the country's goal of building a "beautiful China." Achieving the 2060 carbon neutrality target requires improvements in vehicle energy efficiency, transportation structure optimization, and clean energy transition, leading to significant pollutant and emission reductions and air quality improvement.

02 Enhancing the leading role of standards and technologies and increasing control of vehicle emissions from internal combustion engines (ICEs)

Continuously tightening emission standards, particularly for NO_X reduction by introducing ultra-low NO_X limits for HDVs and promoting the development of more efficient engines and after-treatment technologies with ultra-low emissions, are crucial. Future emission standards should focus on technology-neutral and fuel-neutral emissions, with a particular emphasis on regulating and inspecting real-world vehicle emissions. Consideration can also be given to regulating additional pollutants such as ammonia (NH_3) and formaldehyde (HCHO) alongside tightening the emission limits of regulated pollutants like NO_X and total hydrocarbon/non-methane hydrocarbon (THC/NMHC), and exploring the synergistic control of greenhouse gas emissions.

03 Clean and low-carbon energy transition for the transportation sector can heavily promote the green development of the automotive industry

Clean and low-carbon energy transition in the transportation sector is a fundamental measure for achieving multi-pollutant control and synergistic CO2 reduction. For the LDV sector, promoting the large-scale adoption of electric vehicles to take full advantage of their life-cycle carbon reduction and operational cost benefits is crucial. For commercial vehicles (CVs), diverse technological demands of NEVs should be considered based on comprehensive CV types and operational behaviors. Comprehensive studies on the environmental benefits and costs for different operational segments are needed to establish clear and appropriate CV development plans, according to different NEV technology advantages. Regulating proper action plans and timescales for electric vehicle or hydrogen fuel-cell vehicle technologies and infrastructure development is important based on the cost and emission reduction potential of these technologies. Integrating data for the energy, industry, and supply chains, such as a full life-cycle emission evaluation platform for city-level or regional-level NEVs and clean energy, can effectively support the long-term development and promotion of NEVs and low-carbon biofuels. The deep integration of energy and transportation systems can powerfully promote the development of intelligent NEV infrastructure systems and intelligent energy systems, such as battery swap networks or smart charging networks, significantly improving the convenience and emission reduction capabilities of NEVs.

04 Strengthening infrastructure development and improving service performance to facilitate green travel systems and optimize freight structure

Policymakers should prioritize public and non-motorized transport modes to promote urban green travel. Transitioning to low energy-consumption, low-emission, and high-efficiency transportation modes is required. The Internet of Things (IoT) and big data technology can contribute significantly to intelligent public transport systems that integrate traveler, vehicle, route, station, and cloud data to achieve better green travel systems. Another target should be the optimization of freight structure by speeding up infrastructure construction, improving service levels, innovating service models, enhancing multimodal transportation capabilities, and establishing a more efficient freight system. The railway and marine sectors could play important roles in mid- and long-distance transport for bulk cargo, while new energy vehicles and conveyor belt systems (also known as belt corridors), should be prioritized for short-distance transportation.

05 Exploring intelligent and innovative solutions for managing vehicle emissions in the era of the IoT and big data

Deep emission reduction relies on monitoring of vehicle emissions, real-time inspection of road traffic, and intelligent transport management. The technologies combining intelligent sensing and big-data, such as remote OBD integrated with link-based emission inventories, will play critical roles in future smart management systems. Cities will increasingly adopt powerful advanced technologies, such as 5G, artificial intelligence, big data, and cloud computing to develop innovative, green and low-carbon high-efficiency transportation modes. Comprehensive supervision and an optimized transportation system that integrates vehicles, roads, and cloud data can be expected. Upgrading existing platforms which apply a "sensing-decision" methodology to incorporate "digital, internet-connected, and intelligent" technology, will provide a smart path for improving air quality and achieving carbon peak and neutrality targets.

01 CHAPTER

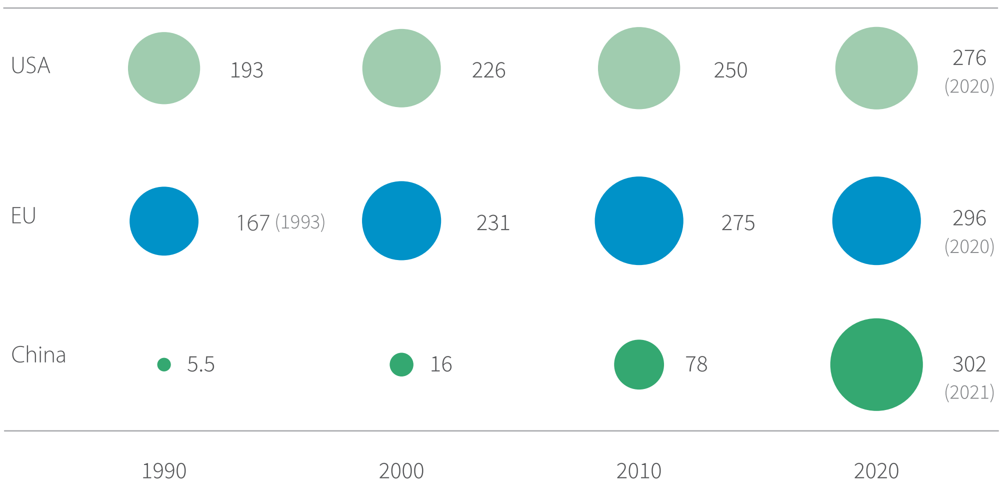
Background

Background

Since the 21st century, due to rapid socioeconomic development and urbanization, China's vehicle stock has experienced significant increase. In 2000, the vehicle stock in China was only 16 million (excluding motorcycles), accounting for less than 7% of the vehicle stocks in the USA or EU (Fig. 1.1). However, by the end of 2021, China's vehicle stock exceeded 300 million, with an average annual growth rate of 15%, making China the country with the highest vehicle stock. Currently, the average vehicle ownership density in China has surpassed 200 vehicles per 1000 people, and in some developed cities has exceeded 350 per 1000 people. With ongoing societal development, the number of vehicles in China is expected to continue growing in the future. Several studies estimate that the vehicle stock in China will reach 400-500 million by 2030, posing severe challenges in transportation, energy, climate, and the environment.

Fig. 1.1. Vehicle population (without motorcycles) in China, the United States of America (USA) and the European Union (EU) during 1990-2021

▼ Comparison of total automobile population (Unit: million)



In recent years, the contribution of vehicle emissions to air pollution has become increasingly prominent in China's megacities. Official results of the source apportionment of fine particulate matter ($PM_{2.5}$) pollution indicate that in megacities such as Beijing, Shanghai, and Shenzhen, mobile source emissions are the leading contributor among all local sectors (Fig. 1.2). Vehicle emissions also contribute to regional and city-wide O_3 pollution (Fig. 1.3) and high NO_2 concentrations in urban areas with heavy traffic. Vehicle emission control has become a major task for air quality management in China and is essential for improving air quality and reducing public health risks.

Fig. 1.2. Contributions of mobile sources to ambient $PM_{2.5}$ in typical megacities in China

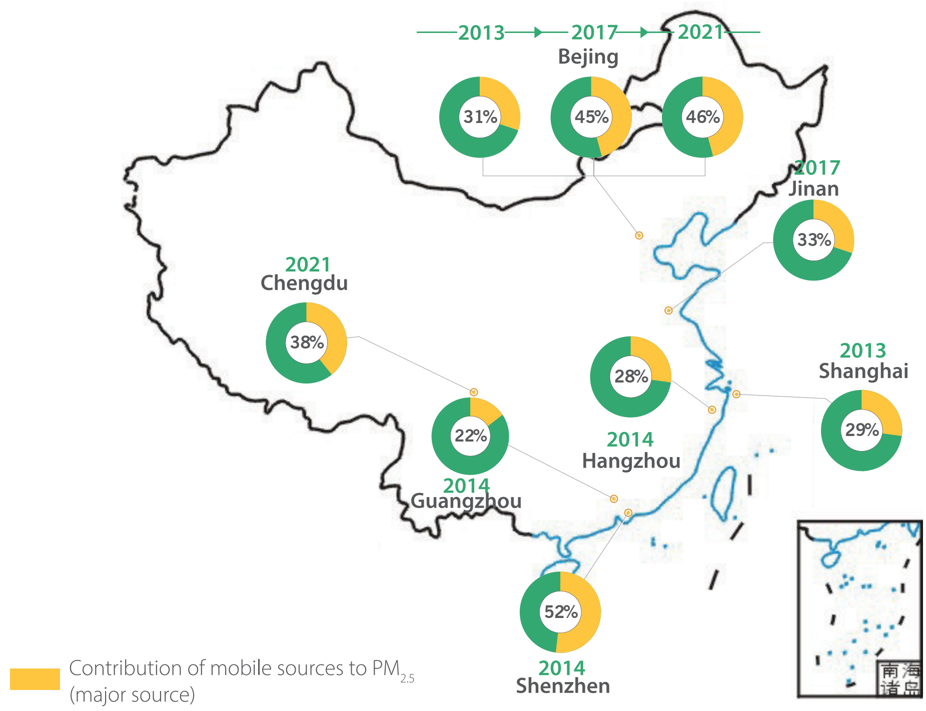
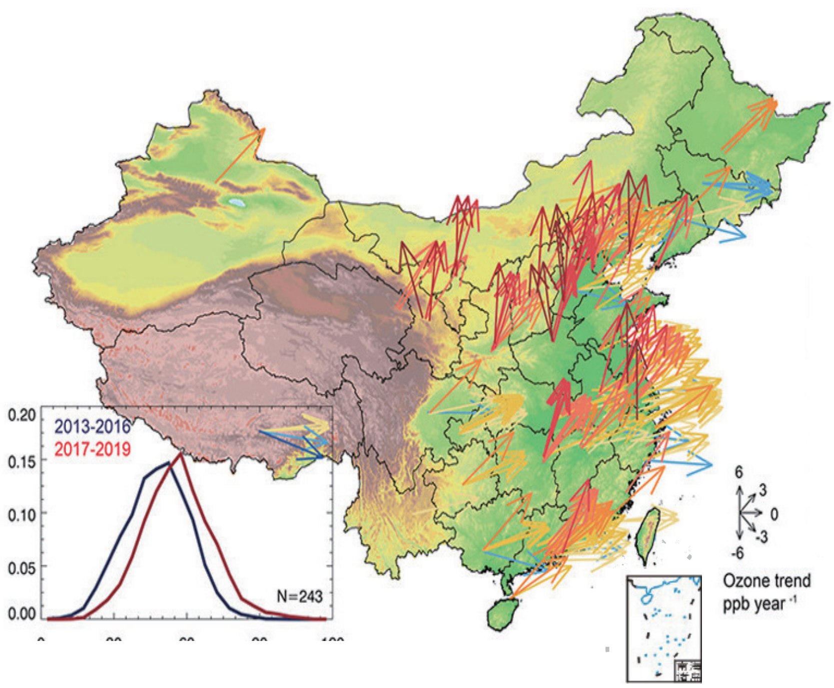


Fig. 1.3. Variations in the maximum daily 8-h average (MDA8) O_3 concentration in summer over China during 2013-2019 (Lu et al., 2020)



In 1994, Tsinghua University led a group of institutions to launch a project called "China's Strategies for Controlling Motor Vehicle Emissions" (commonly known as the B-9-3 project) with support from the World Bank Group. This project conducted large-scale vehicle emission measurements for the first time in China and concluded that the country's vehicle emission control level was 10-20 years behind that of developed countries such as the USA and EU countries. The project aimed to learn from the experiences of the USA and the EU regarding controls for new vehicles, in-use vehicles, and fuel quality, and accelerate the improvement of vehicle emission control in China. In 2000, China officially implemented the China 1 emission standards for light-duty gasoline vehicles (LDGVs) (GB 18352.1-2001), equivalent to the Euro 1 standard implemented by the EU in 1992, marking the initiation of systematic national-level vehicle emission control. Over the past 20 years, China has gradually established an integrated control system of "vehicle-fuel-traffic" by tightening fuel and new vehicle standards, strengthening in-use vehicle inspections, promoting new energy vehicles (NEVs), and implementing comprehensive traffic control measures. China has fully implemented the China 6/VI vehicle emission standards and fuel quality standards and established a supervision system for in-use vehicles by integrating various advanced techniques. China has also actively promoted the optimization of freight transportation and transportation energy structures, positioning itself as one of the leading countries in promoting NEVs worldwide. Despite the rapid increase in the vehicle population, China has effectively mitigated vehicle emissions, reducing the gap between its vehicle emission control levels and those of the USA and the EU.

Megacities play a critical role in promoting vehicle emission control in China. With a high concentration of vehicles, policymakers in megacities are motivated to reduce vehicle emissions and improve air quality. The experiences gained in megacities can expedite the implementation of control policies at the national level more efficiently. For instance, Beijing has been a pioneer in integrating "vehicle-fuel-traffic" controls over the past 20 years, implementing actions such as prohibiting leaded gasoline in 1997 and adopting the China 1 emission standards for LDGVs in January 1999. These actions were later adopted by the central government after one to two years. Shanghai has taken the lead in promoting public transport systems and diversifying transportation energy. Furthermore, Shenzhen became the first city in the world to achieve complete electrification of bus and taxi fleets, establishing a comprehensive industrial layout for NEVs. Finally, Chengdu has developed a smart data-driven system by utilizing traffic big data transmitted from intelligent transportation systems to manage vehicle emissions in urban areas. These cities have carried out vehicle emission control practices according to their unique characteristics, providing valuable first-hand experiences for China.

With the support of the Energy Foundation, this study systematically reviewed the development of vehicle emission control in China over the past 20 years. Specifically, the study analyzed the local vehicle emission control experiences of four representative megacities: Beijing, Shanghai, Shenzhen, and Chengdu. The study aims to provide beneficial experiences and important lessons to other domestic and international cities for controlling vehicle emissions and, more importantly, exploring pathways for transitioning China's transportation sector into a green and low-carbon sector.

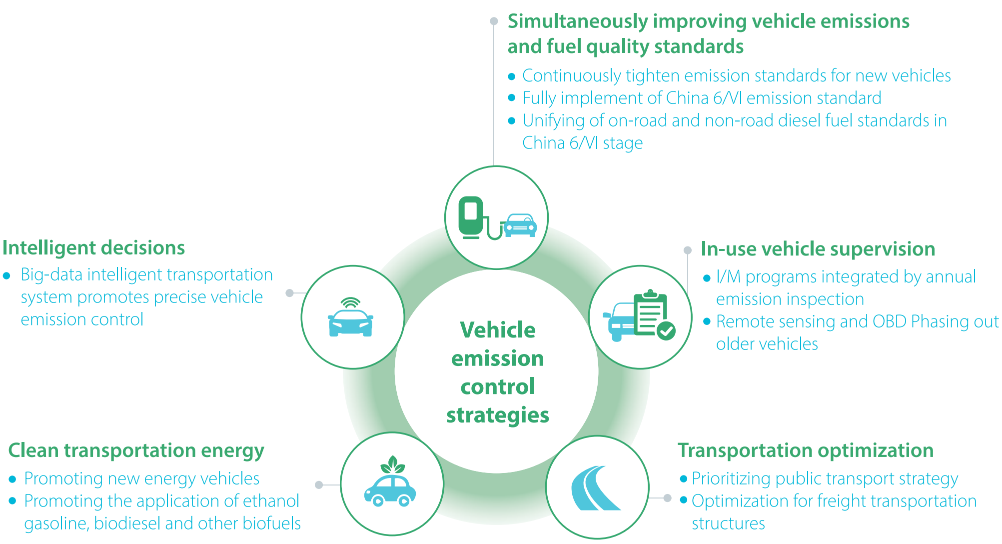
source: Pixabay

02 CHAPTER

A review of vehicle emission control in China during the past 20 years

Since the mid-1990s, China has conducted various systematic studies and practices to establish the integrated "vehicle-fuel-traffic" emission control system. This system includes the continuous upgrading of standards for new vehicles and fuel, the implementation of policies for in-use vehicles, and traffic management policies. In recent years, to promote air pollution control, the country has implemented several national-level plans and measures, such as the "Three-Year Action Plan of Blue-Sky Defense," the "Action Plan for Battle Against Diesel Truck Pollution," and the "Action Plan for Optimization of Freight Transportation Structures." All these actions require more advanced controls on vehicle emissions across China. To date, advanced programs on vehicle emission control have focused on the transformation of energy structures, optimization of freight transportation structures, and reinforcement of dynamic in-use vehicle regulations. As a result, China has developed a more comprehensive and efficient vehicle emission control system (Fig. 2.1).

Fig. 2.1. The integrated "vehicle-fuel-traffic" emission control system implemented in China



2.1

Continuous upgrading of emission standards for newly registered vehicles

Emission standards for newly registered vehicles are a core component of the emission control system. These standards not only reduce emissions from new vehicles but also continuously improve the overall emission control level as the entire fleet is upgraded. China has been promoting stricter emission standards for new vehicles over the past 20 years. In July 2019, the China VI emission standards for heavy-duty natural gas vehicles were implemented, followed by the implementation of these standards for LDVs and HDVs (including buses, sanitation vehicles, and postal vehicles) in July 2020. The complete implementation of the China VI emission standards for heavy-duty diesel vehicles (HDDVs) in July 2021 marked China's entry into the sixth stage of vehicle emissions standards, bringing it closer to control levels adopted in developed countries such as the EU and the USA.

The China 1 emission standards for LDGVs were implemented in 2000 and gradually tightened every three to five years, eventually evolving into the China 6 emission standards. The implementation schedule of the emission standards for LDGVs and HDDVs at the national scale and within typical cities over the past 20 years is shown in Fig 2.2. Compared to the China 1 emission standards, the emission factors of various pollutants in the China 6 emission standards decreased by approximately 95-98%. Table 2.1 presents the emission limits for major pollutants at each stage of the emission standards for LDGVs. Notably, the latest China 6 emission standards adopt the Worldwide harmonized Light vehicle Test Cycle (WLTC), which represents real-world driving conditions more accurately than other test cycles and is expected to narrow the gap between laboratory measurements and real-world emissions. Additionally, a real-drive emission (RDE) test was introduced to strengthen the monitoring of real-world emissions. The new emission standards have also enhanced the evaporative emission control systems used to monitor VOCs, including the addition of a 48-hour test procedure to monitor evaporative emissions and the refueling process.

Fig. 2.2. Implementation schedule of emission standards for light-duty gasoline vehicles (LDGVs) and heavy-duty diesel vehicles (HDDVs) nationwide and in typical cities

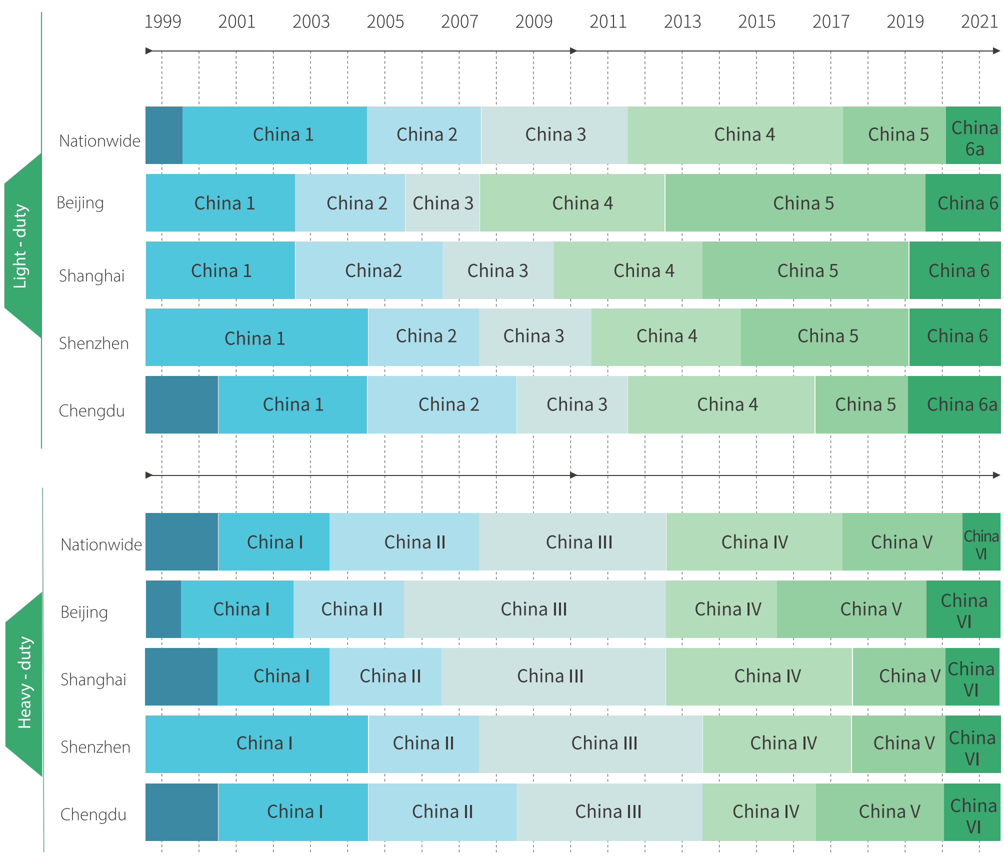


Table 2.1.Emission limits for emission standards of light-duty gasoline vehicles (LDGVs)

Emission standards		CO	THC	NMHC	NO_X	N_2O	PM	PN
		mg/km	mg/km	mg/km	mg/km	mg/km	mg/km	#/km
China1	GB 18352.1-2001	2720	$HC+NO_X$ 970			-	140[1]	-
China2	GB 18352.2-2001	2200	$HC+NO_X$ 500			-	80[1]	-
China3	GB 18352.3-2005	2300	200	-	150	-	50[2]	-
China4		1000	100	-	80	-	25[2]	-
China5	GB 18352.5-2013	1000	100	68	60	-	4.5	$6.0x10^{11}$
China6a	GB 18352.6-2016	700	100	68	60	20	4.5	$6.0x10^{11}$
China6b		500	50	35	35	20	3	$6.0x10^{11}$

Note: 1. Non-direct injection compression combustion engine; 2. compression ignition engine

Similar to the emission standards for LDGVs, the emission standards for HDDVs have also been gradually tightened from China I to China VI standards (Fig. 2.2). Table 2.2 provides the emission limits for each emission standard of HDDVs. The current China VI standards for HDVs not only tighten the emission limits for pollutants but also regulate emission levels under different driving conditions. The engine test cycles were adjusted from the European Steady-state Cycle (ESC) and European Transient Cycle (ETC) to the World Harmonized Steady-state Cycle (WHSC) and World Harmonized Transient Cycle (WHTC), which include the low-speed, low-load operating points and cold-start test requirements. Out-of-cycle emission tests, such as the World Harmonized Not-To-Exceed (WNTE) test and real-world emission test using portable emission measurement systems (PEMS), are required for type-approval conformity. Valid data representative of real-world driving conditions are also required for NO_X concentration calculations. Additionally, the adoption of PEMS in the inspection and compliance programs for new and in-use vehicles, along with type-approval tests, ensures more accurate monitoring. The China VI standards are the first national standards worldwide to propose remote on-board diagnostics (OBD) supervision. These standards have revised the technical requirements for OBD, including monitoring items, conditions and thresholds. This remarkable leap indicates that China's vehicle emission standards are becoming more advanced, moving beyond simply replication or adaptation of EU standards. Notably, China's own experiences and strategies in vehicle emission control are reflected in future emission standards.

Table 2.2. Emission limits for emission standards of heavy-duty diesel vehicles (HDDVs)

Emission standards		CO	HC	NO_X	PM	Smoke	NH_3	PN
		g/kWh	g/kWh	g/kWh	g/kWh	m^{-1}	ppm	#/km
China I	GB 17691-2001	4.5	1.1	8.0	0.61[1]	-	-	-
China II		4.0	1.1	7.0	0.15[1]	-	-	-
China III	GB 17691-2005	2.1	0.66	5.0	0.10	0.8	-	-
China IV		1.5	0.46	3.5	0.02	0.5	-	-
China V	GB 17691-2018	1.5	0.46	2.0	0.02	0.5	-	-
China VI		1.5	0.13	0.4	0.01	-	10	8.0×10^{11}

[1]<85 kW

2.2

Quality upgradation and diversity of fuel

1 Upgrades to fuel quality standards

Fuel quality has a direct impact on vehicle emissions and is a key factor in implementing stricter emission standards for new vehicles. Over the past 20 years, China has gradually tightened the limits on automobile gasoline and diesel fuel through national standards, as shown in Tables 2.3 and 2.4. For instance, the China 5/V fuel standards for both gasoline and diesel were implemented nationwide in 2017, requiring a sulfur content of less than 10 ppm. This is consistent with the requirements for diesel in the EU and Japan and stricter than the maximum limit of 15 ppm in the USA. Additionally, limits for benzene, aromatics, and alkenes have been tightened. The China 6 standards, implemented in 2019, set the alkene content in gasoline to be less than 18% and the aromatic content to be less than 35%. For diesel, the China VI standards limit the polyaromatic hydrocarbon (PAHs) content to be less than 7%. These requirements effectively reduce the emissions of toxic organic pollutants and mitigate risks to human health.

Table 2.3. National standards for automobile diesel fuels

Fuel standards		Maximum Sulfur (ppm)	Maximum PAHs (%)	Maximum FAME (%)	Date of implementation
China I	GB 252-2000	2000	-	-	2002/01/01
China II	GB/T 19147-2003	500	-	-	2003/01/01
China III	GB 19147-2009	350	11	0.5	2010/01/01
China IV	GB 19147-2013	50	11	1.0	2015/01/01
China V	GB 19147-2013	10	11	1.0	2017/01/01
China VI	GB 19147-2016	10	7	1.0	2019/01/01

Note: polyaromatic hydrocarbon (PAHs); fatty acid methyl ester (FAME)

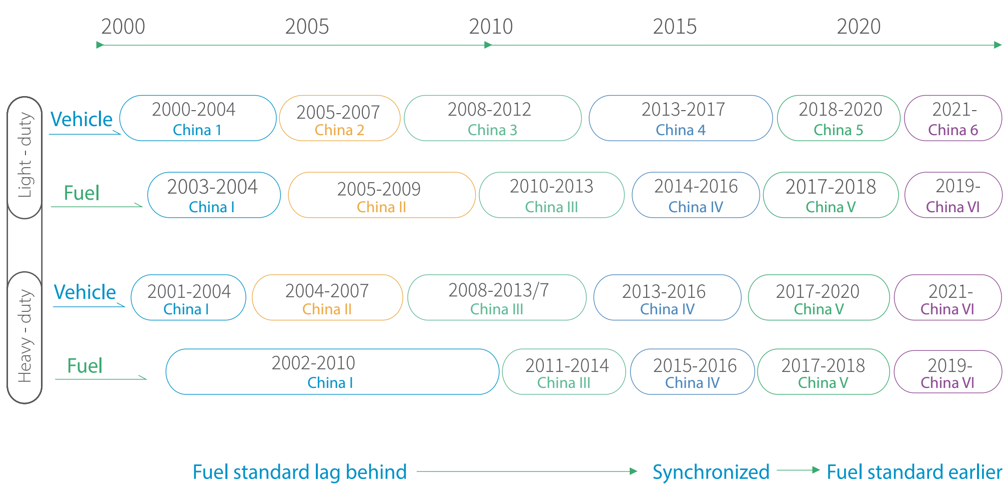
Table 2.4. National standards for automobile gasoline fuels

Fuel standards		Maximum Sulfur (ppm)	Maximum Benzene (%)	Maximum Aromatics (%)	Maximum Alkenes (%)	Date of implementation
China I	GB 17930-1999	1000	2.5	40	35	2000/01/01
China II	GB 17930-2006	500	2.5	40	35	2006/12/01
China III	GB 17930-2011	150	1.0	40	30	2011/05/12
China IV	GB 17930-2013	50	1.0	40	28	2014/01/01
China V	GB 17930-2013	10	1.0	40	24	2017/01/01
China VI-a	GB 17930-2016	10	0.8	35	18	2019/01/01
China VI-b	GB 17930-2016	10	0.8	35	15	2023/01/01

Improvements in fuel quality directly contribute to reducing pollutant emissions. Importantly, high-quality fuel quality is a critical premise for the successful implementation of emission standards for new vehicles. Advanced after-treatment devices such as selective catalytic reduction (SCR) and diesel particulate filters (DPF) require low sulfur content fuel to function properly. Without it, these devices could be disabled or even cause damage to the engine. Simultaneously implementing fuel and vehicle standards allows countries to achieve maximum emission control benefits by upgrading vehicle standards. For example, the implementation of China IV HDDV emission standards was postponed from January 2010 to July 2013 because the oil production industry could not supply diesel that was compliant with the China IV emission standards (sulfur content<50 ppm) nationwide. In fact, nationwide supply of China IV diesel fuel was not achieved until the end of 2014, and the delayed supply of low-sulfur diesel affected the progress of diesel vehicles in pollution mitigation and prevention in China.

Learning from the experiences of fuel quality improvement delays, China has strengthened its control over fuel quality and implemented measures to ensure the production of clean oils. The simultaneous implementation of fuel and emission standards was achieved at the China 5/V stage. The integration of fuel standards with on-road and general (non-road) diesel and some vessel fuels was achieved in the China 6/VI emission standards (Fig. 2.3). This laid a solid foundation for the "Action Plan for Battle against Diesel Truck Pollution" launched in 2019.

Fig. 2.3. Implementation schedule of national standards for new vehicles and fuels in China during the past 20 years



2 Pilot application of biofuels

Biofuels play an important role in China's pursuit of cleaner transportation energy. In addition to continuously improving conventional fuel quality, China has also launched pilot applications of biofuels for vehicles. These applications include the promotion of ethanol gasoline produced from corn/aged grain and biodiesel produced from waste cooking oil.

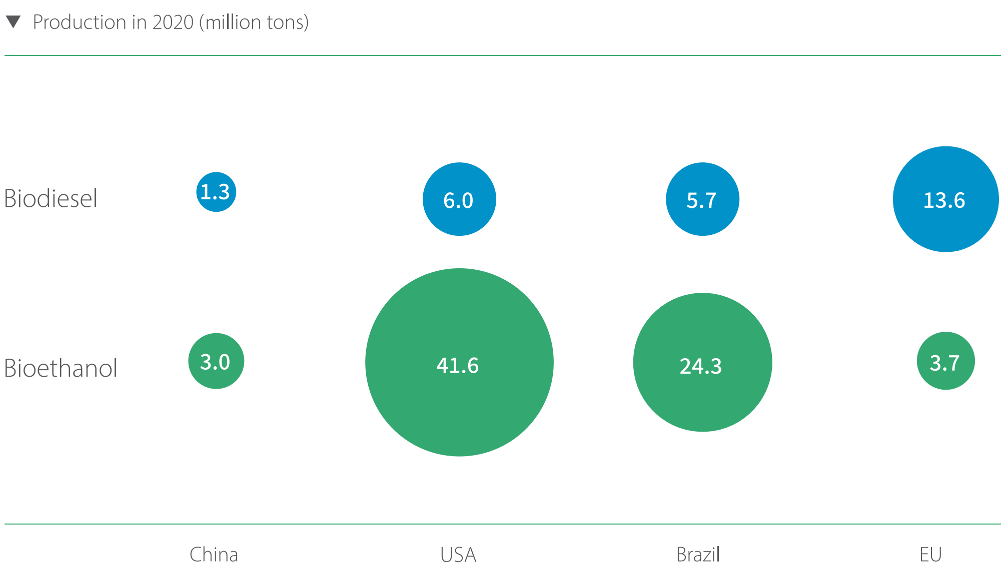
To improve the ecological environment, optimize the energy structure, and address overstocked aged grain, ethanol gasoline has been developed and promoted in the transportation sector in recent years. In 2017, 15 ministries, including the National Development and Reform Commission (NDRC), issued a document to promote ethanol-blended gasoline and deployed an overall layout for the ethanol industry in biofuel production. The goal was to establish an advanced innovation system for biofuels by 2020 and ensure the development of the biofuel ethanol industry catches up with international leaders. A more comprehensive biofuel market is expected to be established by 2025. By 2025, large-scale production of cellulosic ethanol is anticipated with technologies, equipment, and industries for biofuel production reaching leading international levels. Currently, E10 ethanol gasoline (a blend of 10% bioethanol and 90% gasoline) is being sold at various scales in 15 provinces in China, with a bioethanol production of approximately 3 million tonnes (Fig. 2.4).

Fig. 2.4. Promotion of E10 ethanol gasoline in China

Biodiesel, known as "fatty acid methyl (or ethyl) esters" (FAME/FAEE), is derived from various biomasses. Biodiesel offers several advantages, such as good engine starting performance, abundant sources of raw materials, and being a renewable source of energy. The current biodiesel standard in China is the B5 biodiesel standard (GB 25199-2017), which applies to the China 5 and 6 standards. It specifies a volume content of 1-5% for FAME and excludes any additives or pollutants that may cause engine failure. The addition of methanol is also prohibited in these standards. In 2017, the NDRC and eight other departments issued a notice initiating the nationwide supply of China 5 automobile diesel, including the B5 biodiesel. Shanghai conducted a large-scale application of biodiesel made from waste cooking oil in buses, trucks, and other HDVs, resulting in excellent environmental and social benefits (Section 4.2).

It is important to note, the scale of biofuel promotion in China still lags behind leading markets such as Brazil, the USA and the EU. In 2020, bioethanol production reached 41.6 MT in the USA and 24.3 MT in Brazil, while biodiesel production in the EU amounted to 13.6 MT (Fig. 2.5). Therefore, considering China's commitment to reaching its CO_2 emission peak by 2030 and achieve carbon neutrality by 2060, more efforts are needed to promote research and development of biofuels in China.

Fig. 2.5. Comparison of biofuel production in China, Brazil, the European Union (EU) and the United States of America (USA)



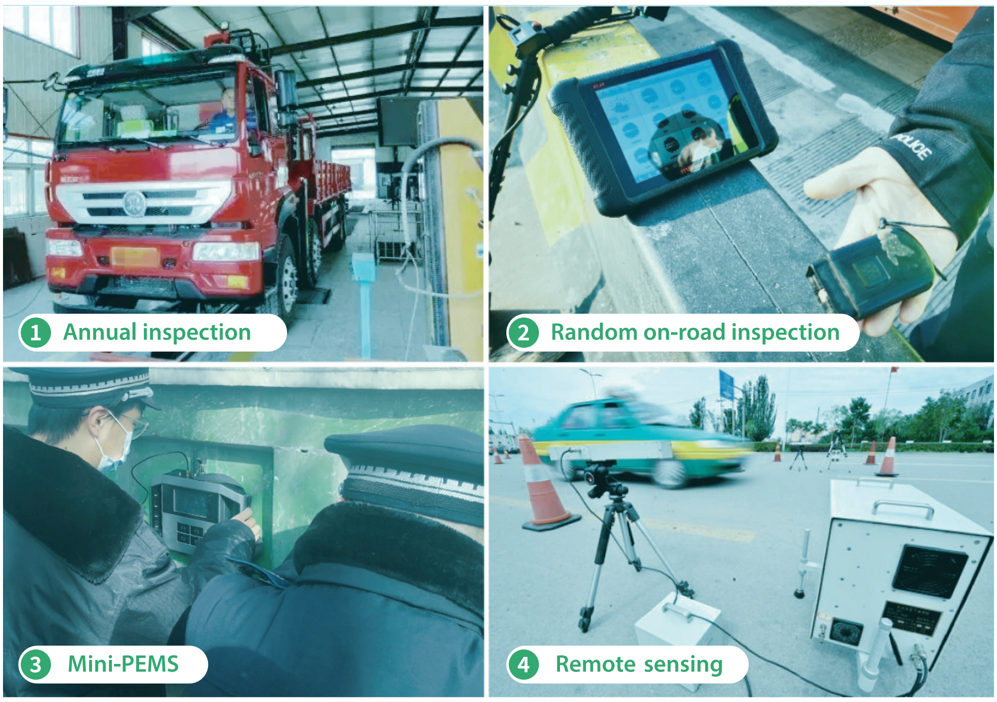
2.3

The in-use inspection and compliance programs

Effectively supervising in-use vehicles is a vital but challenging aspect of vehicle emission control. In recent years, several studies have concluded that real-world emissions from HDVs far exceed the emission limits set by governments, rendering traditional supervision methods ineffective. To strengthen real-world emission compliance of in-use fleets, China has introduced new regulations and standards aimed at combining inspection and compliance programs.

In China, in-use vehicle inspection and maintenance (I/M) programs primarily involve annual emission inspections, mini-PEMS, and remote sensing (Fig. 2.6). In 2017, China established a regulatory method for on-road in-use vehicle inspection by publishing a measurement method and specifications for exhaust pollutants from in-use diesel vehicles using remote sensing (HJ 845-2017). Simultaneously, China continues to improve periodic inspection methods and tighten emission limits. The measurement methods and limits for emissions from diesel vehicles under free acceleration and lug-down cycle (GB 3847-2018) now include NO_X measurements and onboard diagnostics (OBD) inspection. To standardize the supervision of in-use vehicle emissions, China has established a normalized environmental protection supervision mechanism. This mechanism involves stringent measures such as enhanced supervision and management of emission inspection agencies, increased on-road vehicle supervision and sampling tests, and strict penalties for non-compliance. As a result, high-emission vehicles are required to undergo retrofitting and re-inspection within a specified time limit. Failure to comply can lead to listing on the supervision blacklist and legal punishment. These measures have reduced the over-limit ratio of in-use diesel vehicles dropping significantly, from 15% in 2018 to 7% in 2020.

Fig. 2.6. Random emission inspection of on-road heavy-duty vehicles (HDVs)



The "Three-Year Action Plan for the Blue-Sky Defense" and the "Action Plan for Battle Against Diesel Truck Pollution" have set higher emission reduction goals for in-use vehicles. China has implemented more effective, accurate, and comprehensive emission control measures for in-use vehicles by phasing out older vehicles, implementing traffic restrictions, and upgrading supervision technologies. Many provinces in China have encouraged the retirement of high-emission vehicles to promote fleet upgrades and reduce overall emissions. The "Three-Year Action Plan for the Blue-Sky Defense " mandates the phasing out of diesel trucks manufactured before the China IV emission standards, as well as the retirement of old natural gas vehicles using lean burn technology or transitioning from petrol-based vehicles. Nationwide, approximately 3.5 million in-use diesel trucks and vehicles manufactured before the China IV emission standards have been phased out from 2018 to 2020.

Additionally, some cities have adopted measures such as traffic regulations and fiscal incentives to strengthen the supervision of in-use vehicles and reduce the activity of high-emission vehicles. For example, Beijing has gradually tightened restrictions on high emission vehicles and introduced a subsidy mechanism to encourage the replacement of older vehicles (see Section 3.1 for details). Shanghai, with the support of automobile companies, has established a trade-in platform for older vehicles, offering subsidies to vehicle owners who choose to replace their vehicles with NEVs or China VI vehicles.

OBD technology is a new globally adopted approach for emission monitoring. This technology enables the measurement of parameters such as fuel consumption, driving status indices (e.g., speed), and NO_X concentrations in exhaust gas using sensors in SCR systems. The data collected can be stored offline or remotely transmitted to a data platform. China leads in the application of OBD technology and has an effective implementation schedule. The current China VI-a emission standards for HDVs require the full installation of OBD terminals, and the China VI-b emission standards require the transmission of OBD data to the supervision platform starting from July 2023. Some cities such as Beijing and Shanghai, have already implemented pilot measures that incorporate OBD monitoring technology ahead of schedule, yielding positive results (see Section 3.2 for details).

2.4

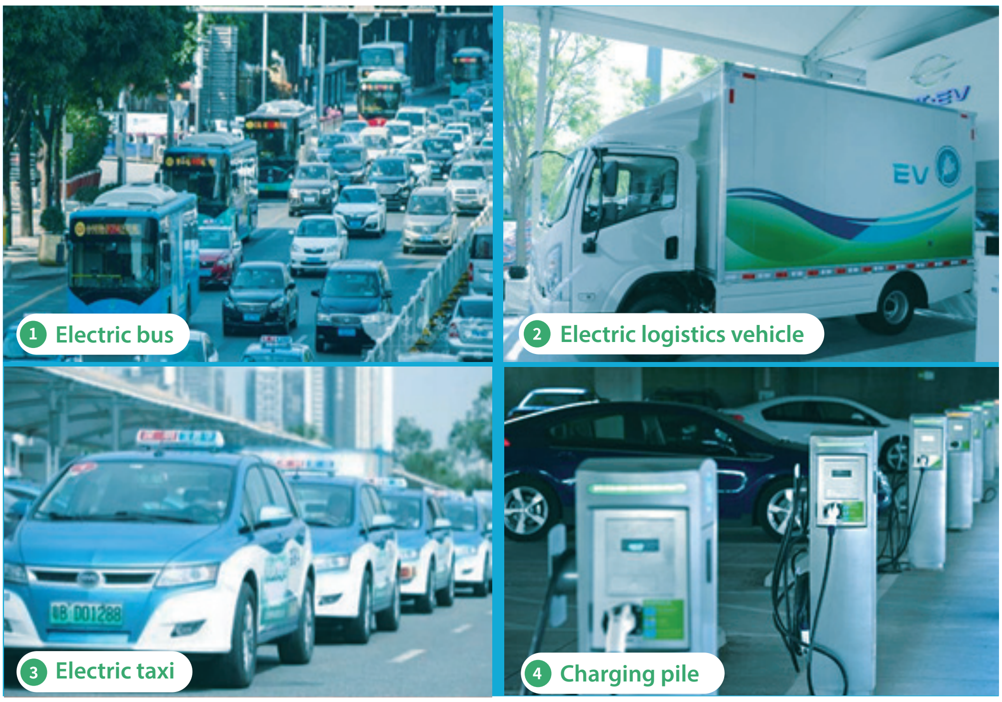
Promotion of new energy vehicles (NEVs)

NEVs play an important role in establishing sustainable and environmentally friendly transportation systems in green and low-carbon cities worldwide. They can achieve ultra-low or zero emissions during vehicle usage making them highly effective in reducing emissions from internal combustion engine vehicles (ICEVs) in urban traffic congestion. Furthermore, as renewable electricity becomes more prevalent in the energy mix, promoting of NEVs allows for the absorption of renewable electricity, greenhouse gas reduction, and improvement of regional air quality. This promotion also ensures the diversification and utilization of low-carbon and clean energy in the transportation sector.

In China, the development of NEVs has gone through several stages of public demonstration (2009-2013), subsidy-driven growth (2014-2018), and subsidy reduction (2018-2020).Currently, NEVs are experiencing a new phase of market-driven growth. Throughout these stages, China has implemented various measures to promote NEVs and has become the largest producer and seller of NEVs globally. These measures include purchase subsidies, tax exemptions, infrastructure construction, and Corporate Average Fuel Consumption-New Energy Vehicle (CAFC-NEV) standards. As of the end of 2020, the NEV stock reached 4.92 million, accounting for 40 % of the total global NEVs and demonstrating sustained rapid growth.

In 2009, the Ministry of Science and Technology, Ministry of Finance, National Development and Reform Commission, and Ministry of Industry and Information Technology jointly launched the "Ten Cities, Thousand New Energy Vehicles" demonstration project. This initiative aimed to encourage NEV development by financially subsidizing the introduction of 1,000 NEVs in each of the selected cities, spanning various sectors, such as public transportation, taxis, municipal services, and postal services. Following a successful three year pilot phase, the program was expanded nationwide, establishing a solid foundation for the development of the NEV industry in China. As shown in Fig 2.7, at present, 25 pilot cities have been promoted, with Beijing, Shanghai, and Shenzhen making outstanding contributions to the adoption of NEVs.

Fig. 2.7. Demonstration of new energy vehicles in the form of electric buses, taxis, logistics vehicles, and charging points



Building upon the experiences of the first stage, China has continued to implement policy incentives to facilitate NEV development. Tax exemptions and purchase subsidies have been introduced to reduce the cost gap between NEVs and ICEVs, stimulate consumer interest in NEV purchases, and promote their market uptake. However, as NEV technologies have matured and the market has rapidly grown, the subsidy amounts have gradually declined. As depicted in Table 2.5, subsidies have been phased out over time. Local subsidies were limited to no more than 50% of national subsidies in 2017, and various technical indicators such as energy density and vehicle energy consumption rate adjustment coefficients were introduced to encourage long-range and energy-efficient NEV models. In 2018, the basic subsidy standard was further reduced, whereas the subsidy for long-range vehicles was increased slightly; in 2019, the subsidies were reduced significantly, and local subsidies were abolished altogether. In 2020, the subsidy period was extended to 2022, and subsidies are expected to decrease by 10%, 20%, and 30% annually (Table 2.5).

Table 2.5. Subsidy standards for new energy vehicles in China during 2016–2021 (unit: 1000 CNY)

	Range of pure electricity, R (mode-test, km)					
Year	100 - 150	150 - 200	200 - 250	250 - 300	300 - 400	>400
2016	25	45	45	55	55	55
2017	20	36	36	44	44	44
2018-transition	14	25.2	25.2	30.8	30.8	30.8
2018	-	15	24	34	45	50
2019-transition	-	1.5	2.4	20.4	27	30
2019	-	-	-	18	18	25
2020	-	-	-	-	16.2	22.5
2021	-	-	-	-	13	18

	Adjustment coefficient of energy density of power battery system (Wh/kg)					
Year	<90	90 - 105	105 - 125	125 - 140	140 - 160	>160
2016	0	1	1.1	-	-	-
2017	0	1	1	1.1	1.1	1.1
2018	0	0	0.6	1	1.1	1.2
2019	0	0	0	0.8	0.9	1
2020	0	0	0	0.8	0.9	1

*Note: subsidies for electric passenger vehicles (CNY/vehicle) = Min {Mileage subsidy standard, Vehicle charge×400 CNY} × Adjustment coefficient of the energy density of the power battery system × Adjustment coefficient of vehicle energy consumption

China has placed great importance on demonstrating the use of NEVs in public fleets, particularly in the electrification of taxis, buses, sanitation vehicles, and urban logistics vehicles. The electrification rate of city buses in China increased from 20% in 2015 to 60% in 2020. Numerous cities have announced their NEV promotion targets for public transportation and set schedules for complete electrification. Shenzhen achieved complete electrification of its taxi and bus fleets as early as 2018. Beijing aims for a 50% electrification rate among new sanitation vehicles, buses, and taxis. Shanghai and Tianjin planned to upgrade all buses to NEVs by 2020. Building on the success of these city demonstrations, the "National Development Plan for New Energy Vehicle Industry" (released in 2020) sets a minimum NEV proportion of 80% in key areas for public transportation, such as buses, taxis, and logistics vehicles from 2021 onwards.

China has implemented various policies to accelerate and standardize the development of supporting NEV infrastructure. The establishment of convenient and comprehensive charging infrastructure plays a vital role in alleviating range anxiety for electric vehicle owners and enhancing the convenience of electric vehicle use. Measures have been taken to clarify the proportion of parking spaces reserved for charging facilities in public parking lots and propose the establishment of a well-distributed charging facility service system that includes residential parking spaces, public and temporary roadside parking spaces, and charging and battery-changing stations. Local governments are required to incorporate the construction and renovation of charging facilities and power grids into city planning, providing policy support for land use and necessary subsidies for construction and operation.

To promote energy-saving, emission reduction, and sustainable development in the automobile industry, China has formulated the CAFC-NEV plan, which pushes automobile manufacturers towards NEV production. The CAFC-NEV plan was officially implemented in April 2018 and revised in July 2019. The proportion of NEV credits required has increased annually and is expected to reach 18% by 2023. The plan incentivizes automobile enterprises to prioritize NEV production by offering benefits such as improved NEV credits and reduced Corporate Average Fuel Consumption (CAFC) levels. This has prompted traditional automobile manufacturers to explore fuel-efficient vehicles and NEVs, thereby increasing the opportunities for the domestic NEV sector and accelerating the development of China's NEV industry.

China is currently entering a new stage in building a modern energy system, which is essential for the transition to low-carbon energy. In the future, NEVs will continue to play a pivotal role in pollution control, carbon reduction, and energy structure optimization, further propelling their rapid growth in China. The 14th Five-Year Plan of the Modern Energy System released by the NDRC and NEA highlights vigorous NEV promotion in public transportation and other sectors, aiming for NEV sales to account for approximately 20% of the total market by 2025.

2.5

Transportation optimization measures

With advancements in vehicle emission control, optimizing transportation systems through the development of green travel options for residents and adjusting freight transportation structures becomes essential for effective energy conservation and emission reduction in the transportation sector.

1 Development of a green public transportation system

In recent years, China has placed great importance on the development of public transport systems and the promotion of non-motorized and green travel alternatives. During the 12th Five-Year Plan, China issued the Guideline for Priority Development of Public Transport, which confirmed developing public transport as a national priority.

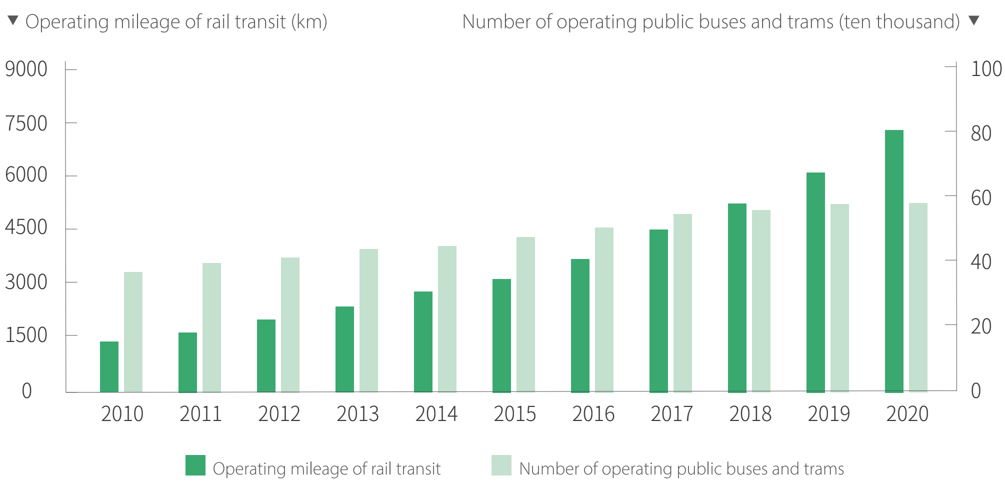
Local governments have implemented a series of policies to expedite public transport under this guidance. These measures include formulating scientific plans for network construction across various public transportation modes, accelerating the construction and upgrading of public transport infrastructure such as transfer hubs, bike lanes, and sidewalks, and ensuring adequate land use for public transport facilities. Simultaneously, efforts are required from both the government and the market. On one hand, the government should continuously increase investments in public transport construction, with funding being incorporated into the public finance system for all cities. On the other hand, market mechanisms should be introduced to reform the investment and financing system for public transport, including expanding investment channels. Additionally, enhancing the accessibility and convenience of public transport should be prioritized by giving right-of-way to public buses, accelerating the development of intelligent transportation systems, and providing mobile payment systems.

The "Prioritizing Public Transport" strategy has yielded remarkable results. By the end of 2015, China had over 630,000 public buses, with operational lanes spanning approximately 900,000 km, marking a 38% and 41% increase, respectively, compared to the numbers in 2010. Currently, the total length of China's bus rapid transit (BRT) system exceeds 3,000 km (Fig. 2.8), with bus-only lanes covering 8,500 km. The annual passenger capacity of public buses has surpassed 90 billion, a 25% increase since 2010. The coverage rate of bus stops within a 300-meter radius in built-up areas is approximately 85%. Rail-based transit is also available in 25 cities in China, and the total length of subway lines in operation exceeds 3,200 km, more than doubling the figure from 2010.

Fig. 2.8. Bus rapid transit (BRT) system in Beijing (left) and Jinan (right) in China

In 2016, China's Ministry of Transport issued an outline for public transport development during the 13th Five-Year Plan, aiming to establish an initial modern public transport system by 2020. Different development indicators have been formulated for cities of varying population sizes including, the sharing rates of public and non-motorized green travel, as well as passenger satisfaction. These measures involve the creation of "bus cities," accelerating the development of intelligent bus application systems and improving the non-motorized transport environment. By the end of 2020, China's rail-based transit mileage reached 7,000 km, five times higher than in 2010, and the number of buses in operation increased by 57% (Fig. 2.9). Cities with populations exceeding one million achieved complete bus stop coverage within a 500 m radius in their built up areas. The sharing rate of non-motorized green travel in central urban areas of megacities, such as Beijing and Shanghai exceeded 70%. Notably, densely-populated megacities have made remarkable progress in public transport development, like Shanghai and Beijing having subway operating mileages exceeding 700 km (see Section 4.1 for Shanghai's "Prioritizing Public Transport" strategy), and subway networks in Guangzhou, Shenzhen, Chongqing, Chengdu, and Wuhan surpassing 300 km in length.

Fig. 2.9. Development of public transport in China during 2010-2020



2 Optimization of the freight transportation structure

The freight transportation volume in China has experienced rapid growth over the past two decades, making China the world's largest contributor to freight transportation. For years, on-road trucks have dominated the freight transportation volume, accounting for over 70%. In contrast, the proportion of railway transportation has steadily decreased, dropping to 7.7% between 2008 and 2016. Given the lower energy consumption and pollutant emissions per unit of freight turnover in waterways and railway systems compared to on-road trucks, promoting a modal shift by increasing the proportion of railways and waterways can effectively reduce air pollution and CO_2 emissions. Optimizing the transportation structure holds great significance in achieving both vehicle emission mitigation, especially for heavy-duty trucks, and implementing supply-side structural reforms.

In 2017, the Central Conference on Economic Work proposed a plan to "optimize the freight transportation structure by reducing on-road volumes and promoting railway transportation." The Ministry of Environmental Protection, in collaboration with relevant ministries and municipal governments, launched the "Work Plan for Air Pollution Control in Beijing, Tianjin, and Hebei and their surrounding areas" which proposed using freight rail for coal delivery and discharge in the ports of Tianjin, Hebei, and the Bohai Rim region. As part of this plan, the ports along the Bohai Rim region were prohibited from accepting coal transported by heavy-duty trucks. In 2018, the "Three-Year Action Plan of Blue-Sky Defense" was proposed; this plan promoted the optimization of the transportation structure as a core technique for mitigating the pollution caused by heavy-duty trucks and establishing a green transportation system. This involved implementing modal freight shifts such as "road to rail" and "road to water" for bulk cargo transportation in the Beijing-Tianjin-Hebei region, the Yangtze River Delta, and the Fenwei Plain. Other national-level actions included improving and upgrading railway and waterway transportation, accelerating the development of multimodal transport systems, and integrating multi-source information. A series of economic and construction measures were implemented, accompanied by structural optimization plans. Among these measures, enhancing the cost advantage of railways and promoting the construction of special railway lines played crucial roles.

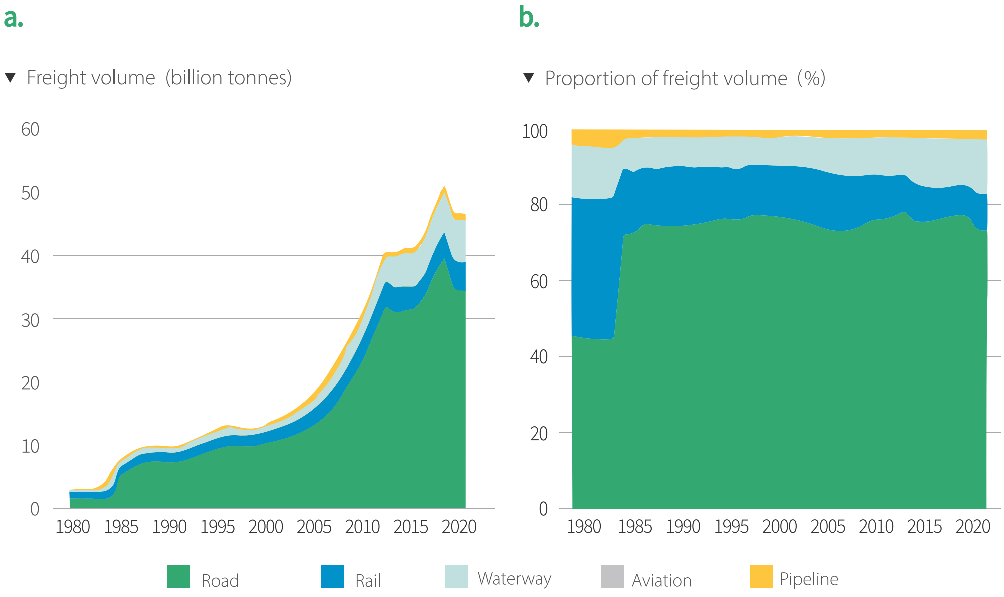
Economic incentives, such as cost reductions and subsidies, have encouraged enterprises to participate in the "road-to-rail" modal shift. The China Railway Group has implemented multiple measures and generated profits of approximately ¥60 billion for enterprises and cargo owners by reducing electrification surcharges and various expenses. In 2019, several railway lines reduced the freight prices of ore and coal by approximately 30%. Municipal governments in Jiangsu and Yunnan also implemented subsidy policies to encourage the modal shift from road to rail for bulk and container cargo transportation.

Accelerating the construction of special railway lines has been instrumental in overcoming the "last kilometer" challenge and improving railway transportation efficiency. The Ministry of Transport (MOT), in collaboration with eight other departments, has identified and proposed 270 construction projects, including connecting-port railways and special railway lines for large logistics parks and industrial and mining enterprises such as coal, steel, electrolytic aluminum, electric power, coking, and automobile manufacturing companies. The Ministry of Natural Resources has prioritized land approval for the construction of special railway lines. The NDRC has further facilitated the planning, investment, construction, and operation of these special railway lines. However, delays in approvals and funding have

affected the progress of some projects. With ongoing efforts to optimize the transportation structure, the transportation capacity of special railway lines is expected to be gradually realized during the 14th Five-Year Plan period (2021-2025), leading to a further increase in railway freight volume.

Driven by the implementation of the "Three-year Action Plan," China's freight transportation structure has been gradually optimized. Railway freight volume has increased from 3.69 billion tonnes (8%) in 2017 to 4.46 billion tonnes (10%) in 2020, with an average annual growth rate of 7%. In contrast, the proportion of on-road truck freight volume decreased from 78% in 2017 to 74% in 2020 (Fig. 2.10). Notably, the transportation structure for bulk cargo in coastal ports has undergone significant optimization, particularly for coal. Coal delivery in ports around the Bohai Rim and the Yangtze River Delta regions as well as Shandong Province (e.g., Tangshan and Huanghua ports), has shifted to railway and waterway transportation. Consequently, the proportion of ore discharge from ports via railways and waterways has increased by 20% since 2017. Truck congestion on roads surrounding the ports has been alleviated. Additionally, intermodal "rail-water" freight transportation, especially for containers, has steadily increased in the region (33% by 2020).

Fig. 2.10. Trend of freight volume and structure in China for 1980-2020



BOX 2-1

Optimization of transportation structure in Beijing, Tianjin, Hebei, and their surrounding areas

The Beijing-Tianjin-Hebei (BTH) region and its surrounding areas serve as important routes for coal and ore transportation. Local heavy industries, including metallurgy, construction materials, and petrochemicals, require frequent delivery and discharge at ports leading to increased demand for bulk cargo transportation, particularly by on-road trucks. As the national pilot area for transportation structure optimization, the BTH areas have implemented nine major projects since 2017. Key areas for conducting the "road to rail" adjustment and intermodal transportation include logistic facilities, industrial or mining enterprises, and yards with railway access. Additionally, the construction of special railway lines for ports has been promoted.

Moreover, a series of exploratory measures have been implemented. For instance, Tangshan has established a special fund to promote the "road-to-rail" modal shift, with the municipal government allocating ¥600 million as a guiding fund to attract enterprise investment in the construction of special railway lines. Iron and steel enterprises utilizing railways to discharge ore and raw materials are provided with a 2% preferential amount on the production limit during non-heating seasons. The National Railway Beijing Bureau has implemented the "road to rail" modal shift project for transporting sand and gravel in Beijing, offering a 40% preferential subsidy. Hebei has conducted a comprehensive investigation into the demand for the special railway lines from industrial and mining enterprises, ports, and logistics parks, resulting in the identification of 94 construction projects. The Tangshan and Huanghua ports have already put their railway lines into use, enabling the railway transportation of coal delivery and discharge from the ports.

BOX Fig. 2.1. Shui-Cao special railway line (Qian'an mining area–Caofeidian port).

According to research conducted by the Transport Planning Research Institute (TPRI) and Tsinghua University, the railway freight volume in the BTH areas increased by 290 MT (~24%) between 2017 and 2020. Simultaneously, the truck volume at major ports and transport corridors of industrial and mining enterprises significantly decreased (~8%). Notably, the modal shift achieved considerable environmental benefits, reducing 38,000 tonnes of NO_X and 700 tonnes of $PM_{2.5}$.

2.6

Overview of socioeconomic and automotive development in typical megacities

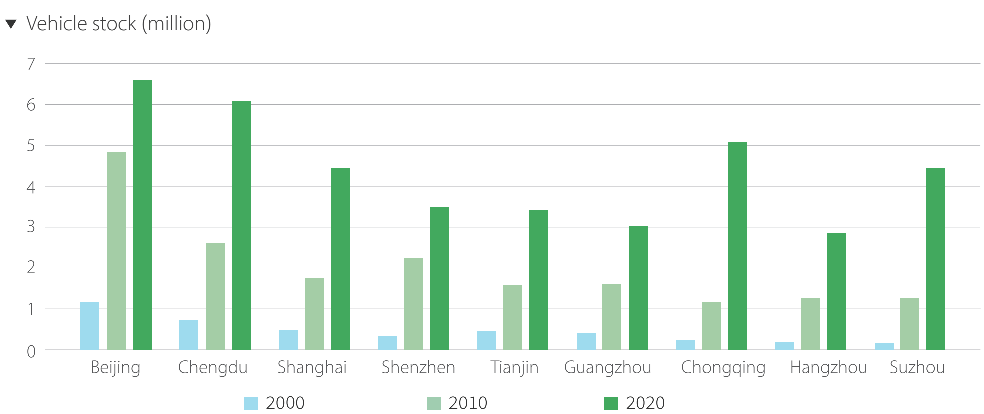
Megacities, such as Beijing, Shanghai, Shenzhen, and Chengdu have experienced rapid economic and social development over the past 20 years, with an average annual GDP per capita growth rate exceeding 8%. This rapid development attracted a large influx of people to these cities, resulting in an annual population growth rate of over 2%, with Shenzhen experiencing a particularly high rate of 4.7% (Fig. 2.11). As a result of the continuous expansion of these cities, the demand for motorized travel has surged, leading to a rapid increase in the number of vehicles.

Fig. 2.11. Economic and demographic conditions of Beijing, Shanghai, Shenzhen, and Chengdu in China

	Area (km²)	Population (million)	GDP per capita (k CNY)	Vehicle population (million vehicles)
Beijing	16,410	21.9 Annually 2.4% ↑	165 Annually 10.0% ↑	6.57 Annually 9.1% ↑
Shanghai	6,341	24.9 Annually 2.2% ↑	157 Annually 8.6% ↑	4.69 Annually 11.5% ↑
Shenzhen	1,997	17.6 Annually 4.7%	158 Annually 8.1% ↑	3.59 Annually 12.5% ↑
Chengdu	14,335	20.9 Annually 3.2% ↑	85 Annually 11.1% ↑	6.03 Annually 11.1% ↑

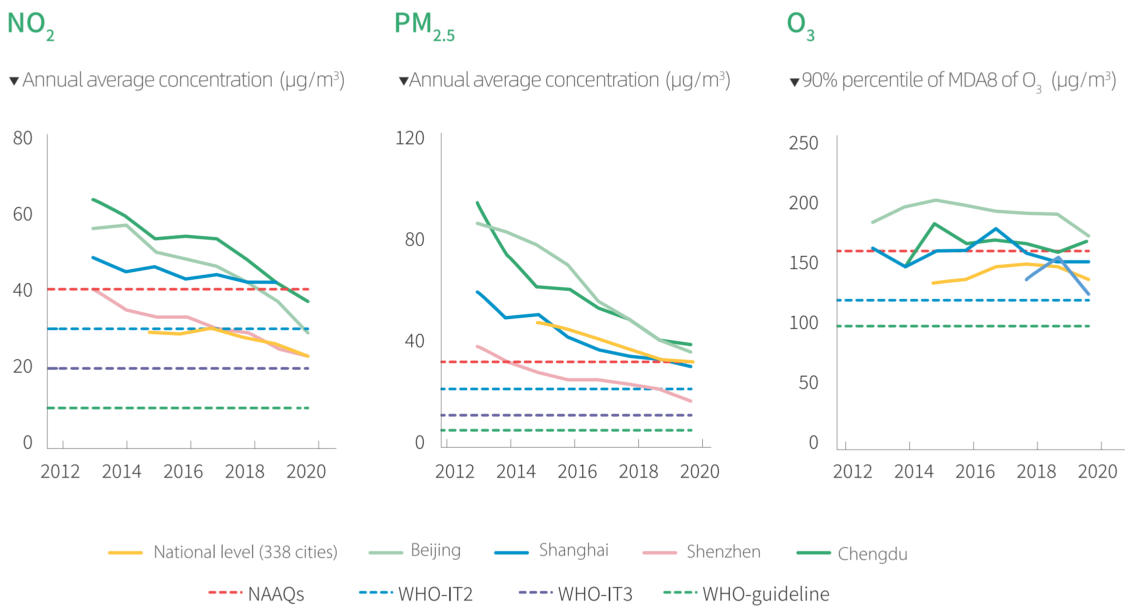
Notably, over the past 20 years, the number of vehicles in China has rapidly increased, with megacities experiencing high concentrations and frequent use of vehicles. The vehicle population in Beijing and Shanghai has exceeded 6 million and 4 million, respectively, despite efforts to control their numbers. Currently, Chengdu has seen an exponential surge in its vehicle population, with, approximately a tenfold increase compared to 2000, as the city had not implemented purchase restrictions at that time. Consequently, Chengdu now has the second-largest vehicle population among all municipal cities in China (Fig. 2.12).

Fig. 2.12. Trends of vehicle population in typical cities of China from 2000 to 2020



Simultaneously, vehicles have become the primary local source of $PM_{2.5}$ pollution in several Chinese cities. In addition, traffic emissions are closely linked to O_3 pollution during the summer while the reduction in NO_2 concentrations in recent years has been unsatisfactory (Fig. 2.13).

Fig. 2.13. Trends of major pollutant concentrations in the four typical cities (Beijing, Shanghai, Shenzhen, and Chengdu) and at the national level



To improve air quality and public health, policymakers in these megacities are heavily motivated to implement strict measures to reduce vehicle emissions, as they play a crucial role in promoting vehicle emission control in China. This study focuses on the characteristics of municipal-level control policies implemented in the four representative megacities in China (Beijing, Shanghai, Shenzhen, and Chengdu) over the past 20 years.

03 CHAPTER

Beijing

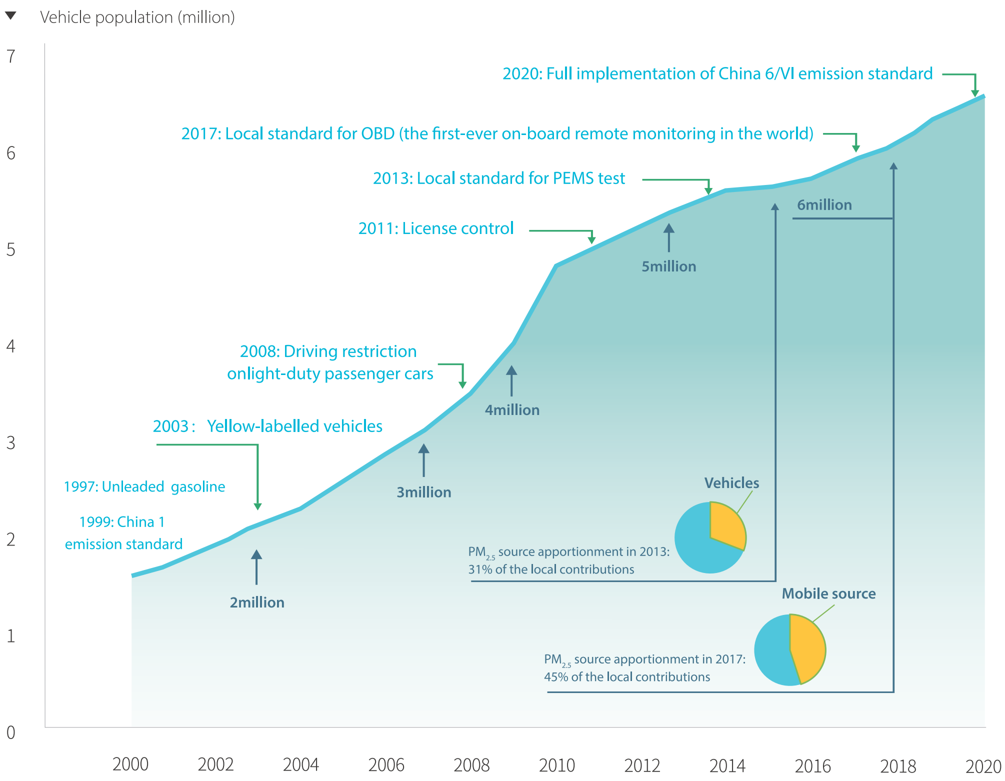
A pioneer city for vehicle-fuel-traffic integrated control

Beijing, the capital of China, has the largest vehicle population among all Chinese cities. In 2020, the vehicle population in Beijing exceeded 6.5 million, marking a 4.2-fold increase compared to 2000 (Fig. 3.1). The vehicle ownership density also rose to 281 vehicles per thousand people. As a pioneer in comprehensive vehicle emission control in China, Beijing has taken the lead in piloting and implementing a series of innovative measures. Notably, Beijing has consistently enforced stricter emission standards for new vehicles even before national requirements were introduced. Other significant control measures include fuel quality improvement, traffic management, in-use vehicle emission control, and promotion of NEVs. Over the past two decades, Beijing has developed an integrated vehicle-fuel-traffic control system that specifically targets vehicle emissions. This model has been widely adopted by many other cities in China. Despite the rapid motorization in recent decades, remarkable progress has been made in mitigating vehicle emissions and improving air quality. In 2021, for the first time, the annual average $PM_{2.5}$ concentration (33 $\mu g/m^3$) met the standard limit of the national ambient air quality standard (NAAQS), which is set at 35 $\mu g/m^3$. This achievement represents a significant milestone in Beijing's decade-long efforts to combat air pollution (see "Beijing Blue" in Fig. 3.2).

Beijing's success in vehicle emission control has played a crucial role in driving nationwide vehicle emission management in China. The country has transitioned to real-world-based emission regulations, that are nearly comparable to the schedules followed by the US and the EU, resulting in a more scientifically-oriented vehicle-management system. Beijing's achievements in controlling vehicular pollution serve as a valuable model for other cities, both domestically and internationally.

Fig. 3.2. Beijing Blue

Fig. 3.1. Growth trend in vehicle population and key moments regarding vehicle emission control in Beijing, 2000-2020



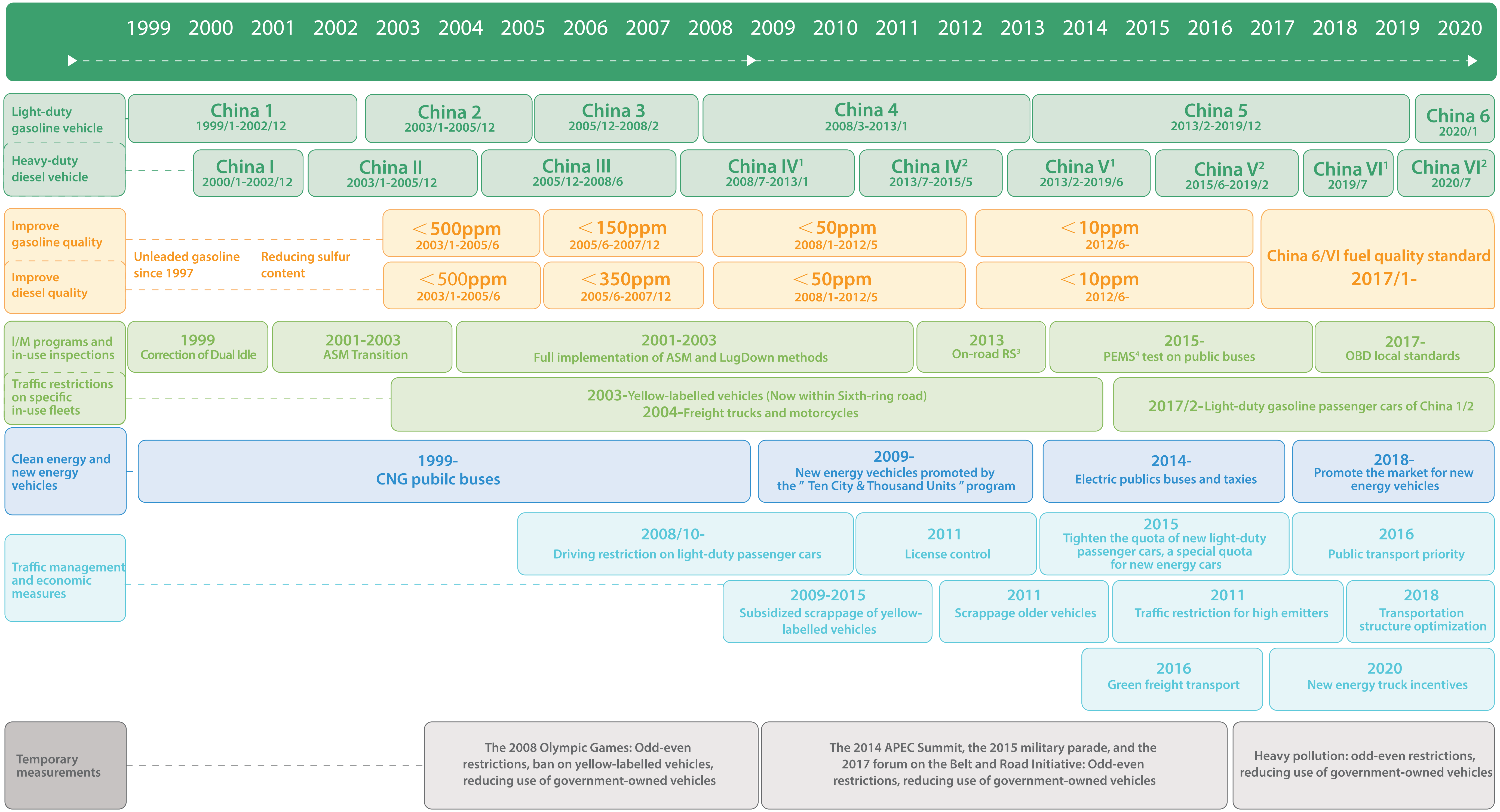
3.1

Remarkable achievements regarding the integrated vehicle emission control

1 A review of the vehicle emission control in Beijing over the past 20 years

The rapid growth of the vehicle population in Beijing poses a substantial challenge to air quality, with the transportation sector being the largest local contributor to $PM_{2.5}$. The 2014 source apportionment showed that vehicle emissions accounted for 31% of the local ambient $PM_{2.5}$ contributions, while subsequent reports in 2018 and 2021 mentioned that 45% and 46% of the local contributions, respectively, originated from mobile sources, including on-road vehicles as the primary sources. Controlling vehicular pollution is essential for improving air quality and mitigating public health risks.

Beijing has formulated and revised over 30 municipal standards since the late 1990s, including the management of new vehicles, in-use vehicles, fuel quality, traffic structures, and economic incentives. The integrated vehicle-fuel-traffic control system (Fig. 3.3) constitutes a solid foundation for Beijing as a pioneer in managing vehicle emissions. Recently, Beijing has placed more emphasis on in-use vehicle supervision, transportation structure optimization, and clean energy transition, dedicated to reducing vehicle emissions and continuously improving air quality.



[1] Only implemented for public fleets; [2] for freight trucks and long-distance coaches; [3] remote sensing test; [4] portable emission measurement system

Fig. 3.3. Review of major emission control measures for on-road vehicles in Beijing, 1998–2020

1. Controls on new vehicle emissions

As the core of the emission control system, continuous updating of emission standards constitutes the largest contribution to emission reductions in Beijing (see Section 3.1.2 and Fig. 3.7). In January 1999, Beijing became the first city in China to implement the China 1 emission standard (equivalent to Euro 1) for gasoline vehicles. Since then, the implementation of more stringent emission standards in Beijing has usually been ahead of other Chinese cities, together with improved fuel quality, which is not often the case elsewhere. In 2013, Beijing released a local standard to adopt PEMS in the type-approval and in-use tests of heavy-duty vehicles. It was the first regulation in China to introduce PEMS for real-world emission tests, making China the third market to shift into real-world monitoring and promote national PEMS regulations. In 2020, Beijing implemented the China 6/VI emission standards ahead of other cities, in accordance with the most stringent regulations in the world.

2. Controls on in-use vehicle emissions

Beijing places great emphasis on the supervision of in-use vehicles, implementing a series of control measures, including I/M programs, phase-out and renewal of older vehicles, and enhancing real-world emission monitoring.

In-use vehicle exhaust detection is at the core of I/M programs. In 1999, Beijing revised the two-speed idle test method and the standard limits for China 1 vehicles. The more stringent acceleration simulation mode (ASM) method was introduced in 2001 and further improved and fully implemented in 2003, with updated tighter emission standards. In addition, the lug-down test has been adopted for in-use heavy-duty diesel vehicles since 2003, while smoke-emission limits were tightened in 2010.

Although the share of public fleets is insignificant in terms of vehicle population, their contribution to total vehicle emissions in Beijing cannot be overlooked due to their high activity levels (e.g., more than 50,000 km and 80,000 km annually for buses and taxis, respectively) and high emission deterioration risks. Thus, Beijing encourages the renewal of high-frequency-use vehicles (e.g., taxis and buses) and promotes the phase-out and retrofitting of key public fleets (e.g., sanitation, postal services, tourism, intercity freight, and construction engineering transportation fleets). Beijing launched the replacement of three-way catalytic converters (TWC) for taxis used for over 2 years in 2016, and approximately 50,000 taxis replaced their TWC systems within 1 year. Additionally, a regular replacement mechanism for TWC was established: A taxi with a TWC that had been used for more than 2 years would be automatically included in the renewal plan.

Furthermore, Beijing introduced an environmental labeling system for in-use vehicles, and environmental labels were issued according to the emission standards and exhaust inspection results. Pre-China 1 gasoline vehicles, pre-China III diesel vehicles, and other vehicles that failed to comply with emission standards were issued yellow labels, whereas other vehicles were issued green labels. To promote phasing out high emitters (i.e., yellow-labeled vehicles), Beijing not only set progressively stricter driving restrictions for yellow-labeled vehicles but also provided subsidies to promote fleet turnover. Thanks to great efforts, Beijing successfully phased out all yellow-labeled vehicles in 2015, becoming the first city in China to address the issue of yellow-labeled vehicles. In 2017, Beijing released a rule prohibiting China 1 and 2 LDGVs from driving within the Fifth Ring Road (i.e., ~1,000 km^2) on weekdays, and China III and older heavy-duty diesel trucks from driving within the Sixth Ring Road (i.e., ~2,500 km^2). The restrictions on heavy-duty diesel trucks were further expanded to cover the entire city in November 2019.

In recent years, Beijing has enhanced real-world emission monitoring, promoted the application of advanced supervision technology, and accelerated the construction of a supervision platform. According to a local standard (i.e., DB11/318-2005) established in 2005 on remote sensing, on-road emissions are monitored with fixed or mobile roadside remote-sensing equipment, and vehicles exceeding the emission standard limits are imposed penalties. With the escalating importance of in-use vehicle supervision and the rapid development of advanced technologies, Beijing pioneered remote monitoring for heavy-duty vehicles and became the first city in the world to adopt remote monitoring OBD technology. Since 2018, Beijing has piloted an OBD retrofit for China IV and V in-use heavy-duty vehicles. Beijing further required the original installation of OBD devices, and regulations regarding the OBD installation and data transmission (in China VI) were implemented in advance. At present, an online monitoring platform with 100,000 in-use heavy-duty vehicles has already been established (Section 3.2).

3. Fuel quality improvement

Fuel quality not only directly affects the vehicle emission levels , but also determines the feasibility and durability of advanced after-treatment devices. Only the simultaneous implementation of fuel standards can maximize the emission control benefits of vehicle emission standards. As early as the 1990s, Beijing began to improve fuel quality and gradually phased out the leaded gasoline and high-sulfur-content fuels in 1998 and 2012, respectively. Notably, Beijing implemented fuel quality standards in the China 2/II-5/V stages ahead of other cities in China, thereby ensuring synchronous implementation of vehicle emission standards. In contrast, the nationwide implementation of emission standards has been delayed several times due to the lagging fuel standards. China 6/VI fuel standards became effective in Beijing in 2017, even before the implementation of the China 6/VI emission standard. After two decades of hard work, fuel quality has been comprehensively improved (Fig. 3.4). The sulfur content of both gasoline and diesel is lower than 10 ppm; olefin and aromatic contents, as well as summertime vapor pressure of gasoline decreases gradually; and the cetane number for diesel also continues to increase, while PAH content decreases.

Fig. 3.4. Improvement of main components of automotive fuel in Beijing over the past 20 years

4. Promotion of clean and new energy vehicles

Beijing has been actively promoting clean energy and NEVs in public fleets, including buses, taxis, sanitation, and postal services. Compressed natural gas (CNG) buses were introduced in Beijing in 1999. During the 2008 Beijing Olympic Games, over 4,000 CNG buses were part of the fleet, making a significant contribution to reducing particle and black carbon (BC) emissions. Since 2009, Beijing has been one of the first "Ten Cities, Thousand New Energy Vehicles" demonstration cities, initiating the promotion of electric vehicles (EVs) in public fleets. Currently, EVs make up 90% of new buses, while clean energy vehicles and NEVs account for over 90% of the bus fleets.

It is important to note that clean energy transformation is not always successful. In 1999, Beijing started promoting LPG taxis and the vehicle population reached approximately 45,000. However, due to multiple reasons such as inconvenient gas-filling facilities, high operating costs, and the lack of emission-reduction benefits, Beijing gradually stopped promoting LPG taxis in 2003 and completely phased them out by 2009. Beijing also introduced a small number of gasoline-natural gas dual-fuel vehicles in the taxi fleet, but similar obstacles prevented their widespread adoption.

To encourage enterprises to transition from in-use diesel trucks to new energy (i.e., electric) trucks, Beijing established relevant policies. In July 2019, Beijing granted right-of-way priority to new energy logistics and distribution vehicles gradually increasing their proportion in freight permits. In August 2020, Beijing strengthened the promotion of new energy light-duty trucks by providing financial incentives to eligible enterprises. Enterprises adopting 20 or more new energy trucks at once were eligible for additional urban freight permits. By 2020, Beijing had successfully promoted 23,000 new energy trucks, and new energy vehicles accounted for 100% of trucks under 4.5 tonnes (excluding trucks for dangerous or frozen goods) with freight permits.

In terms of the private purchase of EVs, Beijing has allocated a separate quota of 60,000 new energy light-duty passenger cars per year and has been increasing the proportion. NEVs are exempt from traffic restrictions on weekdays. As of the end of 2020, the NEV population in Beijing had reached 412,000. The 14th Five-Year Plan sets a target of 2 million NEVs by 2025. To achieve this goal, an average annual growth rate of 37% is required.

5. Traffic management and transportation structure optimization

Beijing improves its transportation structure by optimizing urban planning, developing public transportation, encouraging non-motorized traffic, and implementing traffic-control measures. These measures help mitigate the rapid growth of the vehicle population and reduce milleage activity per car. In terms of rail transport, there were 24 subway lines and 428 stations with a total length of 727 km in 2020 (Fig. 3.5). In contrast, there were only two subway lines before 2000. Regarding the ground public transport system, Beijing prioritizes public buses, accelerates the construction of bus-only lanes, optimizes the bus network, and improves the accessibility and convenience of public transport. Beijing has also encouraged the development of intelligent transportation systems. Currently, there are six types of ground-bus lines: express, microcycle, customized bus, general urban, suburban, and urban suburban connecting lines. In 2020, Beijing had 1,207 bus lines with a total length exceeded 28,000 km. The proportion of green travel in the central urban areas exceeded 75%.

To mitigate the rapid growth, high-frequency use, and highly aggregated distribution of LDGVs, Beijing implemented a restrictive policy in October 2008, which restricted LDGVs from driving one weekday per week. This policy was driven by the successful temporary traffic management during the 2008 Olympic Games. Since 2011, Beijing has employed a lottery-based method to allocate vehicle registration quotas, effectively restricting the growth of the vehicle population and alleviating urban traffic pressure. From 2015 to 2021, the annual quota of new LDGVs was further reduced from 150,000 to 100,000, while the share of NEVs rose continuously reaching 60% in 2021. Several traffic management measures, including the construction of parking spaces, intelligent traffic management, differentiated parking fees, and restrictions on non-local vehicles, have also been implemented, greatly contributing to transportation mode optimization. The travel ratio and intensity decreased for LDGVs, and the annual vehicle kilometers traveled (VKT) decreased from 19,000 to 11,000 km per year.

In recent years, Beijing has actively promoted the optimization of freight transportation structures. In 2018, Beijing issued the Three-Year Action Plan for Promoting Transportation Structure Adjustment, which focused on the "Road to Rail" adjustment of bulk goods transportation, such as commercial vehicles, steel, coal, sand and gravel aggregates, and life necessities. Logistics facilities, industrial or mining enterprises, and yards with railway access were listed as key areas for conducting the adjustment, and a clear railway freight volume quota was allocated to relevant enterprises. Beijing also strengthened the analysis, supervision, and risk warning systems to ensure the implementation of freight structure adjustment. These efforts have led to exciting achievements in the development of innovative green transportation structures. For example, green supply bases for building materials were established around Beijing, with railway transportation as the selection criterion. In March 2020, sand and gravel aggregates were transported from the Weike mine in Miyun District to mixing plants in Daxing District using the railway for the first time. This marked the establishment of a new zero-emission green transportation mode, utilizing railways for long-distance transportation, and NEVs for short-range connections. The railway transportation distance was also reduced to below 150 km. After three years of practice, the proportion of railway freight transportation increased from 6.4% in 2017 to 9.7% in 2020.

6. Economic incentives

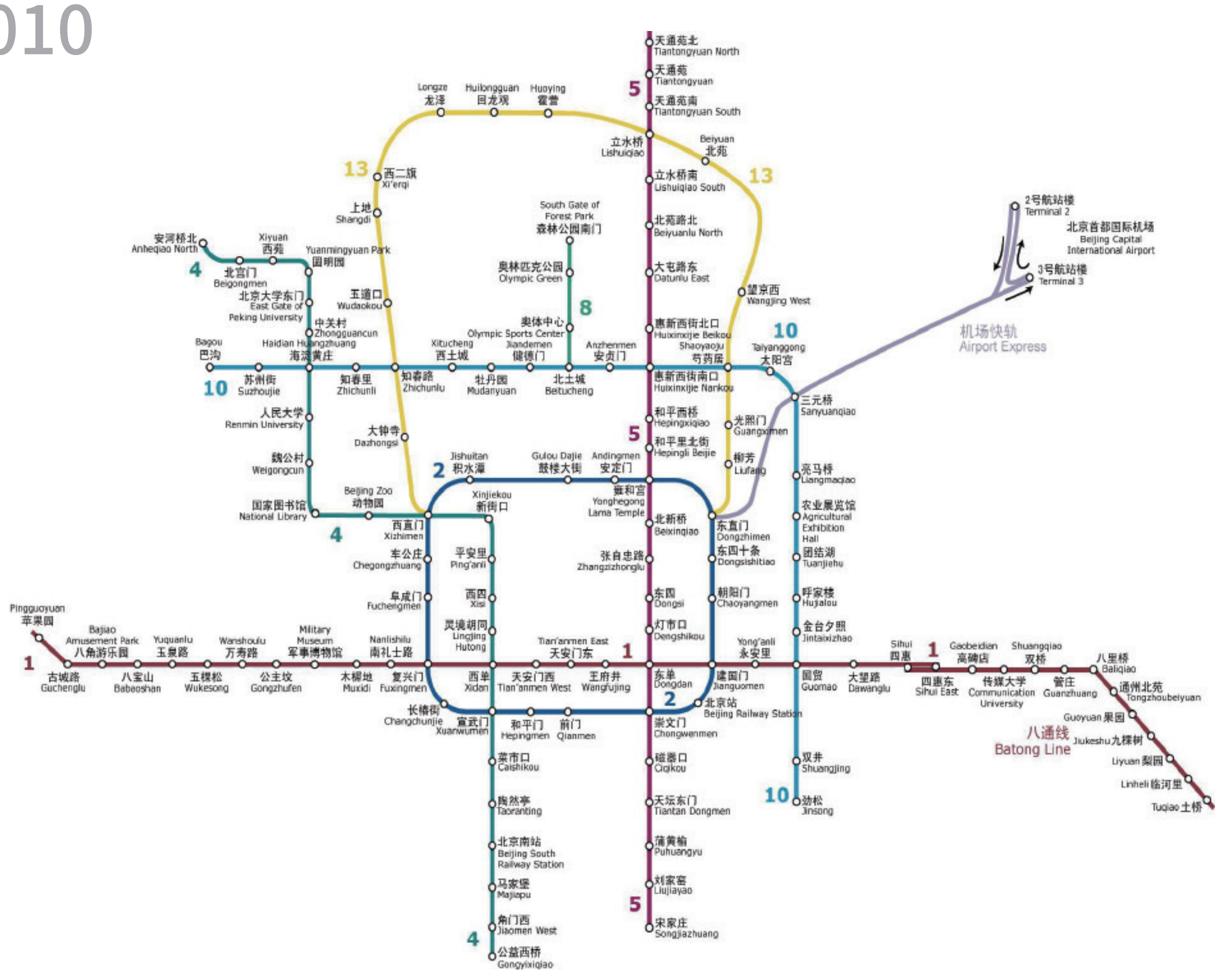
Economic incentives are powerful, particularly when combined with other measures. For example, since 2009, Beijing has been providing subsidies to accelerate the phasing out of yellow-labeled vehicles. The phase-out plan in Beijing was strengthened by offering subsidies to China 1 and 2 gasoline vehicles and China III diesel trucks that were scrapped or transferred outside of Beijing. To further encourage the phasing out of China 3 gasoline vehicles, Beijing introduced a "Plan to Further Promote the Phase-out and Renewal of High-emission Old Vehicles". Subsidies were provided for phasing out China 3 passenger vehicles, with owners receiving compensation 4,000 and 22,000 CNY by the end of 2020. A subsidy-decline mechanism was also developed to promote the earlier phase-out of old vehicles.

To promote the adoption of NEVs, Beijing has provided subsidies for the purchase of NEVs based on national and local subsidy standards. Additionally, an operation incentive policy for new energy light-duty trucks has been implemented. "Green-freight enterprises" that meet the criteria are rewarded with emission-reduction funding and operational conveniences. Beijing has also introduced multiple policies, including differentiated parking fees, construction and operation subsidies for public charging facilities, and priority allocation of freight permits for logistics vehicles. These measures comprehensively enhance the advantages of NEVs.

2000

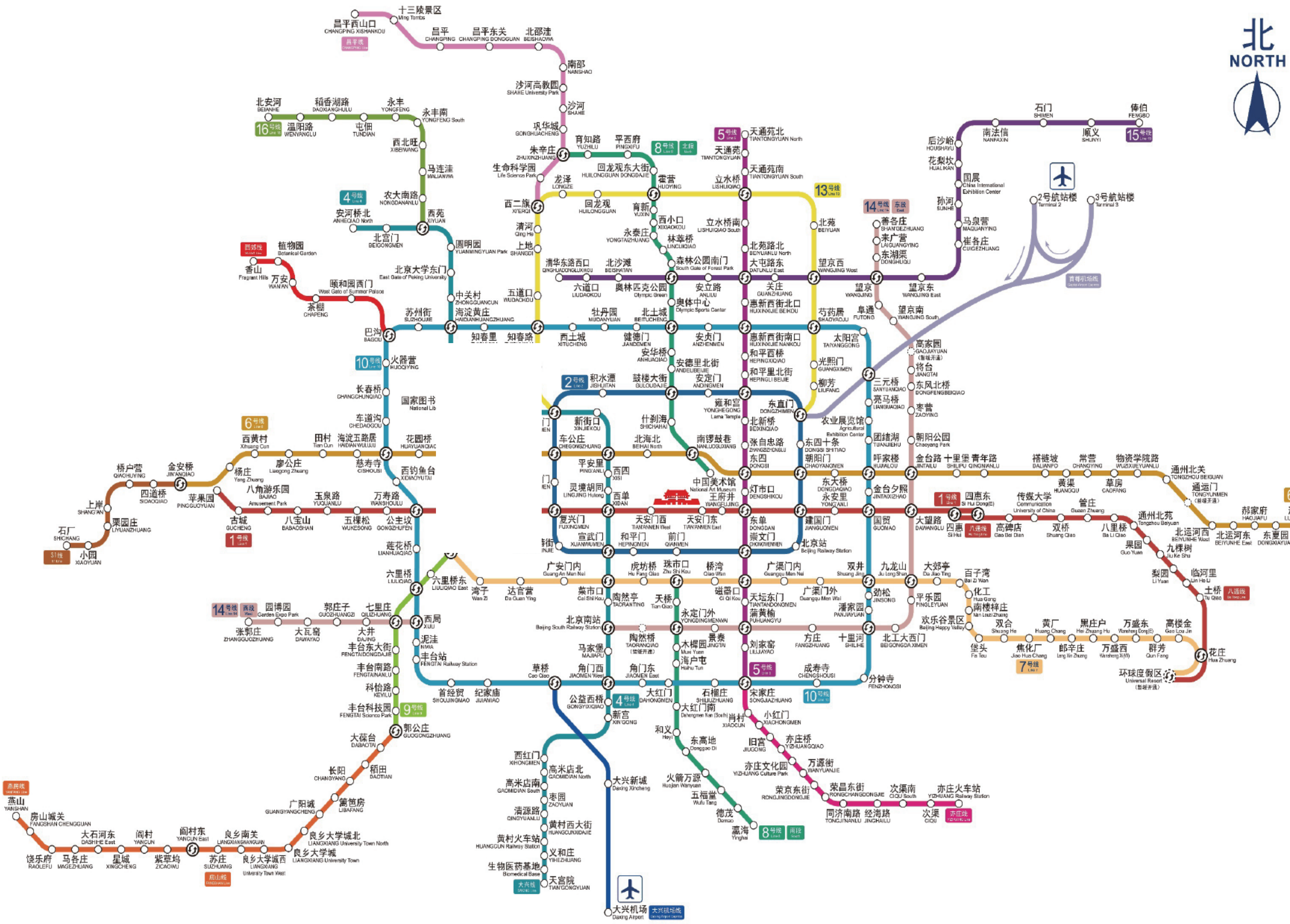
2
Jishuitan 积水潭
Guloudajie 鼓楼大街
Andingmen 安定门
雍和宫 Yonghegong Lama Temple
西直门 Xizhimen
Chegong 车公庄
东直门 Dongzhimen
东四十条 Dongsishitiao
阜成门 Fuchengmen
朝阳门 Chaoyangmen
Pingguoyuan 苹果园
1
Bajiao Amusement Park 八角游乐园
Yuquanlu 玉泉路
Wanshoulu 万寿路
Military Museum 军事博物馆
Nanlishilu 南礼士路
Tian'anmen East 天安门东
Yong'anli 永安里
Sihui 四惠
古城路 Gucheng lu
八宝山 Babaoshan
五棵松 Wukesong
公主坟 Gongzhufen
木樨地 Muxidi
复兴门 Fuxingmen
西单 Xidan
天安门西 Tian'anmen West
王府井 Wangfujing
东单 Dongdan
建国门 Jianguomen
国贸 Guomao
大望路 Dawanglu
四惠东 Sihui Eas
长椿街 Changchunjie
宣武门 Xuanwumen
和平门 Hepingmen
前门 Qianmen
崇文门 Chongwenmen
北京站 Beijing Railway Station

2010



天通苑北 Tiantongyuan North
天通苑 Tiantongyuan
天通苑南 Tiantongyuan South
5
Longze 龙泽
Huilongguan 回龙观
Huoying 霍营
立水桥 Lishuiqiao
Beiyuan 北苑
13
西二旗 Xi'erqi
立水桥南 Lishuiqiao South
上地 Shangdi
South Gate of Forest Park 森林公园南门
北苑路北 Beiyuanlu North
2号航站楼 Terminal 2
北京首都国际机场 Beijing Capital International Airport
3号航站楼 Terminal 3
安河桥北 Anheqiao North
Xiyuan 西苑
Yuanmingyuan Park 圆明园
4
北宫门 Beigongmen
北京大学东门 East Gate of Peking University
奥林匹克公园 Olympic Green
大屯路东 Datunlu East
五道口 Wudaokou
8
望京西 Wangjing West
中关村 Zhongguancun
奥体中心 Olympic Sports Center
惠新西街北口 Huixinxijie Beikou
10
机场快轨 Airport Express
Bagou 巴沟
Haidian Huangzhuang 海淀黄庄
Xitucheng 西土城
Jiandemen 健德门
Anzhenmen 安贞门
Shaoyaoju 芍药居
Taiyanggong 太阳宫
苏州街 Suzhoujie
知春里 Zhichunli
知春路 Zhichunlu
牡丹园 Mudanyuan
北土城 Beitucheng
惠新西街南口 Huixinxijie Nankou
三元桥 Sanyuanqiao
人民大学 Renmin University
和平西桥 Hepingxiqiao
光熙门 Guangximen
大钟寺 Dazhongsi
和平里北街 Hepingli Beijie
魏公村 Weigongcun
Jishuitan 积水潭
Gulou Dajie 鼓楼大街
Andingmen 安定门
柳芳 Liufang
亮马桥 Liangmaqiao
Beijing Zoo 动物园
Xinjiekou 新街口
雍和宫 Yonghegong Lama Temple
国家图书馆 National Library
农业展览馆 Agricultural Exhibition Hall
西直门 Xizhimen
北新桥 Beixinqiao
东直门 Dongzhimen
车公庄 Chegongzhuang
平安里 Ping'anli
张自忠路 Zhangzizhonglu
东四十条 Dongsishitiao
团结湖 Tuanjiehu
阜成门 Fuchengmen
西四 Xisi
东四 Dongsi
朝阳门 Chaoyangmen
呼家楼 Hujialou
Pingguoyuan 苹果园
灵境胡同 Lingjing Hutong
灯市口 Dengshikou
金台夕照 Jintaixizhao
Bajiao Amusement Park 八角游乐园
Yuquanlu 玉泉路
Wanshoulu 万寿路
Military Museum 军事博物馆
Nanlishilu 南礼士路
Tian'anmen East 天安门东
Yong'anli 永安里
Sihui 四惠
Gaobeidian 高碑店
Shuangqiao 双桥
八里桥 Baliqiao
古城路 Guchenglu
八宝山 Babaoshan
五棵松 Wukesong
公主坟 Gongzhufen
木樨地 Muxidi
复兴门 Fuxingmen
西单 Xidan
天安门西 Tian'anmen West
王府井 Wangfujing
东单 Dongdan
建国门 Jianguomen
国贸 Guomao
大望路 Dawanglu
四惠东 Sihui East
传媒大学 Communication University
管庄 Guanzhuang
通州北苑 Tongzhoubeiyuan
长椿街 Changchunjie
宣武门 Xuanwumen
和平门 Hepingmen
前门 Qianmen
崇文门 Chongwenmen
北京站 Beijing Railway Station
Guoyuan 果园
八通线 Batong Line
Jiukeshu 九棵树
Liyuan 梨园
Linheli 临河里
Tuqiao 土桥
菜市口 Caishikou
磁器口 Ciqikou
双井 Shuangjing
陶然亭 Taoranting
天坛东门 Tiantan Dongmen
劲松 Jinsong
北京南站 Beijing South Railway Station
蒲黄榆 Puhuangyu
马家堡 Majiapu
刘家窑 Liujiayao
角门西 Jiaomen West
宋家庄 Songjiazhuang
公益西桥 Gongyixiqiao

2020



Legend

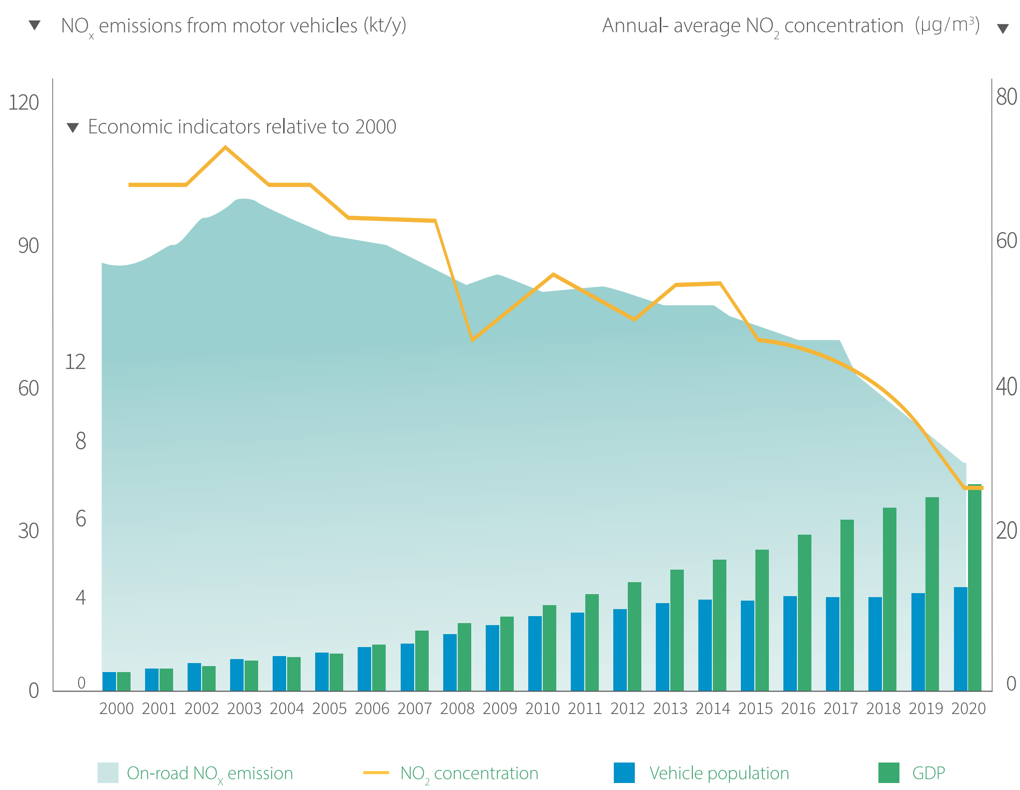
- Line 1 Batong Line
- Line 2
- Line 4 Daxing Line
- Line 5
- Line 6
- Line 7
- Line 8
- Line 9
- Line 10
- Line 13
- Line 14
- Line 15
- Line 16
- Fangshan Line
- Changping Line
- Yanfang Line
- Yizhuang Line
- Xijiao Line
- S1 Line
- Capital Airport Express
- Daxing Airport Express
- Transfer Station

Fig. 3.5. Development of the subway network in Beijing

2 Assessment of vehicle emission-reduction benefits

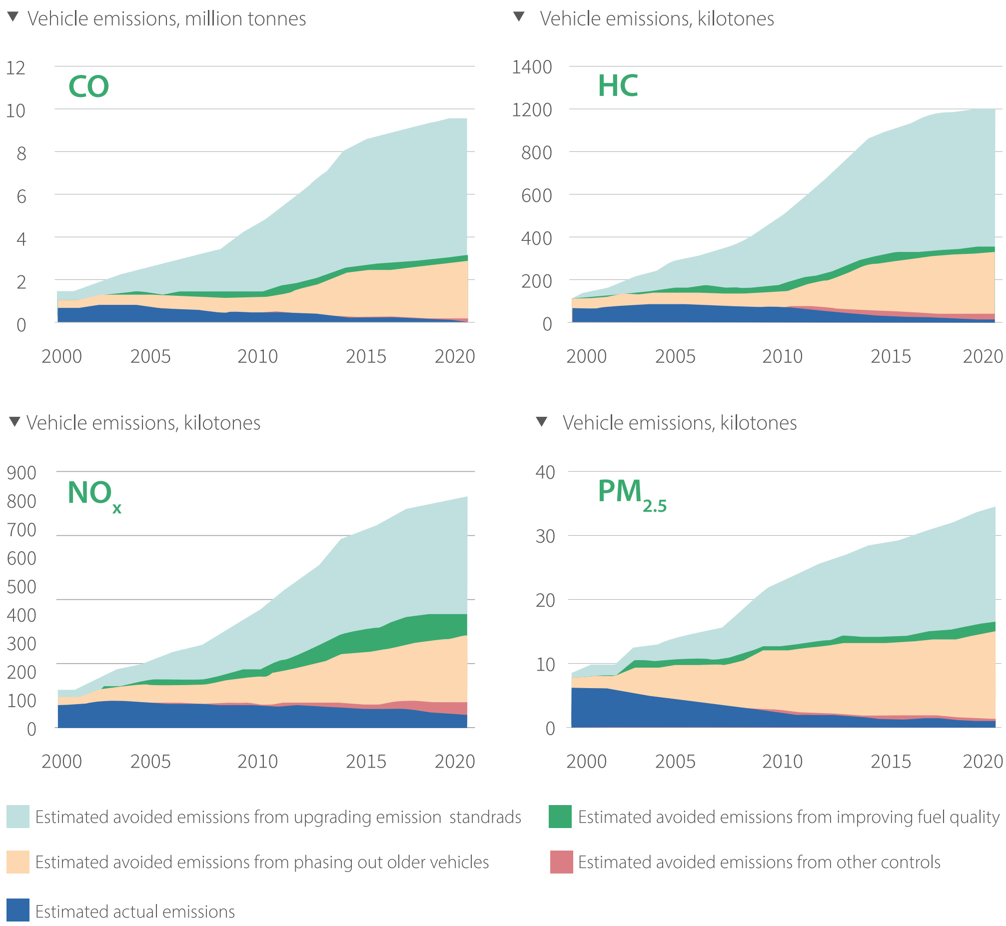
During the past 20 years, Beijing has experienced rapid economic and social development, with a tenfold increase in GDP, a 60% increase in population, and a 320% increase in the vehicle population. However, vehicle emissions have decreased dramatically (Fig. 3.6). In 2020, compared to 2000, the annual on-road emissions of CO, THC, NO_X, and $PM_{2.5}$ in Beijing were reduced by 86%, 70%, 43%, and 86% respectively (Fig. 3.7). This significant reduction has resulted in a considerable decrease in air pollution levels. For example, NO_2 concentrations, closely related to traffic emissions, decreased from 71 to 29 μg/m^3 during 2000-2020. This trend aligns with the decreasing trend of on-road NO_X emissions (Fig. 3.6).

Fig. 3.6. Economic trends and typical air quality indicators in Beijing during 2000–2020



According to assessments, without the implementation of strict vehicle emission control measures, vehicle emissions in Beijing during 2020 would have been 5-15 times higher than those in 2000, causing severe damage to the ecological environment and public health. As shown in Fig. 3.7, the integrated "vehicle-fuel-traffic" control system has resulted in a 94%-99% reduction in on-road air pollutant emissions over the past two decades (based on the ratio of actual to uncontrolled emissions in 2020).

Fig. 3.7. Assessment of vehicle emission reduction in Beijing during 2000–2020



Among the multiple emission control measures, upgrading vehicle emission standards, improving fuel quality, and phasing out older vehicles have played the most important roles. Continuous upgrades of emission standards for new vehicles are estimated to contribute to 70%, 68%, 55%, and 50% of the CO, THC, NO_X, and $PM_{2.5}$ emission reductions respectively (shown in the light blue part of Fig. 3.7). Improving fuel quality directly contributes to 4%, 5%, 11%, and 5% of the CO, THC, NO_X, and $PM_{2.5}$ emission reductions respectively (shown in the green part of Fig. 3.7). Notably, there are also significant indirect benefits such as the timely implementation of fuel quality standards which has ensured the effectiveness of vehicle emission standards. These indirect benefits are included in the contribution of the upgrade of vehicle emission standards. Phasing out older vehicles further reduces emissions from vehicle fleets. From 2000 to 2020, this measure has resulted in approximately 26%, 26%, 31%, and 43% CO, THC, NO_X, and $PM_{2.5}$ emission reductions respectively (shown in the yellow part of Fig. 3.7).

However, the marginal emission reduction benefits from upgrading vehicle and fuel standards have gradually decreased. Therefore, Beijing has implemented a series of integrated management measures, including registration control to constrain the increase in the vehicle population, promotion of public transportation and non-motorized travel modes, the boost of NEVs (i.e., fleet electrification), optimization of freight structures (i.e., "Road to Rail"), and strengthened inspection of in-use vehicles. The benefits of these measures are illustrated in Fig. 3.8. In recent years, the emission reduction benefits of these measures have become more significant and will play an increasingly important role in vehicle emission control in the future.

The constraint on the vehicle population and other traffic optimization measures have effectively reduced vehicle activity levels, especially for light-duty passenger cars, resulting in significant reductions in CO and HC emissions. Due to these two measures, in 2020, CO and HC emissions were reduced by 48 kt and 21 kt, respectively, accounting for 69% and 51% of the total emission reduction benefits from control measures (excluding upgrades of vehicle emission and fuel quality standards and phasing out old vehicles referred to as "other measures").

Fig. 3.8. Assessment of the emission-reduction benefits management (excluding the upgrades of the vehicle emission and fuel quality standards and phasing out the old vehicles)

The benefits of promoting NEVs have also become prominent in recent years. By the end of 2020, Beijing had promoted 412,000 NEVs, including light-duty passenger vehicles, taxis, buses, and urban logistics distribution vehicles. The introduction of NEVs across multiple vehicle categories has resulted in significant emission reduction benefits for all four air pollutants. In 2020, the promotion of NEVs helped reduce CO, HC, NO_X, and $PM_{2.5}$ emissions by 11 kt, 3 kt, 17 kt, and 0.14 kt respectively, accounting for 10%-35% of emission reductions from other measures. With further innovation and development of NEV technology, as well as improvements in infrastructure, services, and safety supervision systems, NEVs will play a vital role in future air quality improvement and carbon mitigation.

Adjusting the transportation structure is key to significantly reducing vehicle emissions, especially for heavy-duty trucks. The implementation of the "Road to Rail" strategy in the Beijing-Tianjin-Hebei region has effectively reduced the excessive reliance on road transportation and mitigated the intensity of travel for diesel trucks. Since the "Road to Rail" action is still in the initial stage, the emission reduction benefits are not yet significant, accounting for only 3%-4% of the emission reduction from other measures. With further enhancement of railway transportation capacity and the construction of railway lines, the optimization of freight transportation structures will thereby continue. This will lead to a significant increase in the volume of bulk goods transported by rail, contributing to energy conservation and improved air quality.

With the increasing vehicle population in Beijing, the inspection of in-use vehicles has become increasingly important. Over the past ten years, strengthened I/M programs and efficient monitoring methods have made significant contributions. In 2015, the supervision of in-use vehicles reduced CO, HC, $NO_{X,}$ and $PM_{2.5}$ emissions by 26 kt, 4 kt, 10 kt, and 0.1kt respectively. Since the introduction of remote OBD monitoring technology in the Beijing V standard, real-world emissions of Beijing V and China VI diesel vehicles equipped with OBD devices have significantly decreased. In 2020, the contribution of in-use vehicle inspection to NO_X and $PM_{2.5}$ emission reduction exceeded 50% (Fig. 3.8) among other measures. The success of OBD monitoring in Beijing is discussed in Section 3.2 as an example of real-world emission monitoring.

3.2

Remote OBD monitoring for heavy-duty vehicles

1 Development of OBD for heavy-duty vehicles in Beijing

Although emission standards have been tightened and emission-control technologies continuously upgraded, it has been reported that real-world NO_X emissions from diesel fleets are significantly higher than the standard limits due to inadequate in-use compliance regulations. A global study published in Nature in 2017 on the environmental impact of diesel vehicles, revealed that real-world NO_X emissions in many countries or regions, including Europe, the United States, China, and Japan, were several times higher than the limits. Several complex issues contribute to high NO_X emissions from diesel vehicles (DVs). First, occasional manufacturer falsifications such as the Volkswagen diesel gate scandal; second, the use of poor-quality urea solution as a reducing agent in selective catalytic reduction (SCR) systems or shielding SCR components to reduce costs; third, automotive companies prioritizing regulatory testing, leading to increased real-world emissions under complex driving or environmental conditions. For instance, NO_X emissions significantly increase during cold starts, low temperatures, and low loads, which are outside the ideal catalytic temperature range of 200-450 ℃ for SCR. As a result, monitoring real-world NO_X emissions from diesel fleets presents a challenge for the control of on-road vehicular pollution.

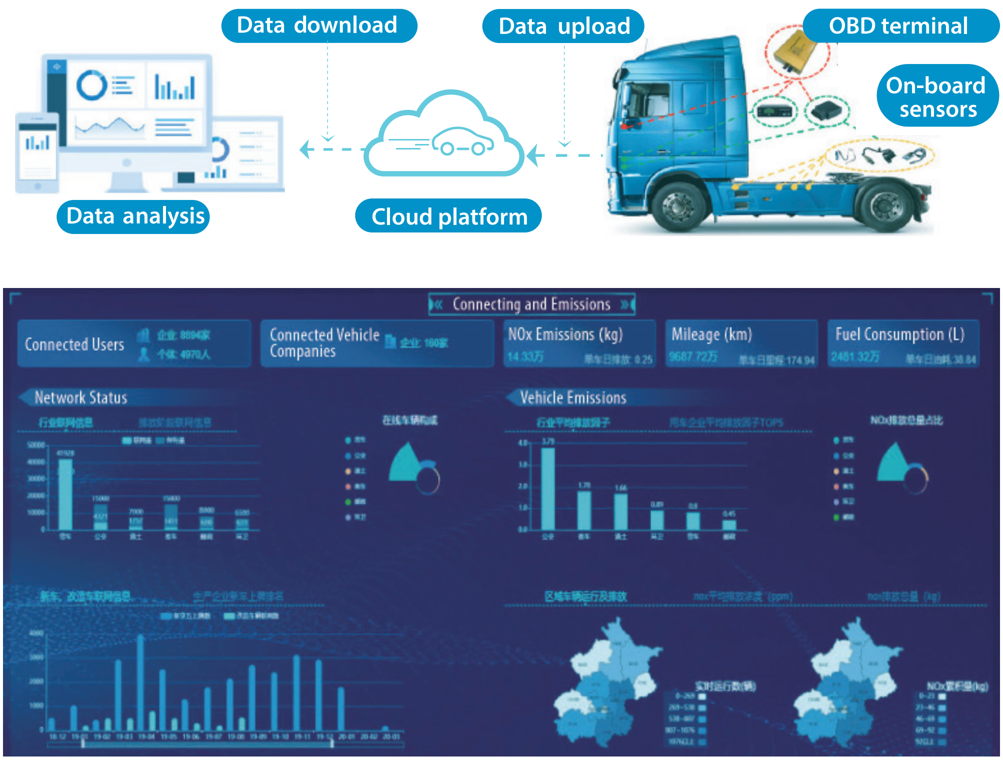
In addition to traditional in-use emission testing methods such as compliance inspection based on dynamometer tests and annual I/M, remote-sensing detection and PEMS testing have been employed to strengthen the management of real-world emissions in Beijing. While these measures have achieved significant accomplishments in diesel-fleet emission control, issues regarding poor timeliness, accuracy, and coverage remain. Consequently, the OBD technology, which integrates intelligent real-world emission supervision and traffic big data, provides a new technical choice for accurate and efficient regulation of in-use diesel vehicles.

Currently, on-board sensor technology for emission monitoring, including NO_X, is relatively mature, and the OBD interface agreement for heavy-duty vehicles has been standardized internationally, promoting the feasibility of remote OBD monitoring. By collecting second-by-second driving conditions such as vehicle speed and engine speed, as well as NO_X concentration data through the OBD terminal, the information can be transmitted to data platforms operated by vehicle manufacturers or regulatory agencies. This adoption of OBD enables real-time remote management of heavy-duty vehicle emissions.

Beijing has been a pioneer in the adoption of remote OBD monitoring technology. In 2017, a pilot project was conducted for online monitoring of emissions and energy consumption of heavy-duty vehicles in the tourism, bus, and freight transport sectors. The Beijing Municipal Environmental Protection Bureau, in collaboration with third-party institutions and vehicle manufacturers, selected 500 HDDVs for retrofitting and demonstration of the application of OBD technology (retrofitted OBD). Furthermore, Beijing released the Limits and Measurement Method of Emissions from heavy-duty vehicles (OBD method phase IV and V), becoming the first city in the world to require remote online monitoring of heavy-duty vehicle emissions and energy consumption throughout their full lifecycle. Since September 1, 2018, all newly sold and registered heavy-duty vehicles in Beijing are required to be equipped with automatic monitoring devices for emissions and energy consumption by original vehicle-equipment manufacturers (OEM-performed OBD), and the collected data must be sent to the Beijing Data Management Platform in real-time. Data quality analysis indicates that the data quality differs significantly between vehicles equipped with OEM-performed OBD and retrofitted OBD, with better data quality observed for vehicles equipped with OEM-performed OBD. Most vehicles had valid data for over 80% of the time. Conversely, vehicles equipped with retrofitted OBD, experienced missing data and issues with data validity, making it challenging to accurately evaluate real-world emissions. Consequently, the OBD monitoring regulations in Beijing mandated the installation of OEM-performed OBD devices for Beijing V heavy-duty vehicles.
Relevant regulations have continuously strengthened. Since January 2020, heavy-duty diesel and gas

vehicles sold in Beijing have required the installation of OBD management terminals. According to a new regulation published in May 2020, local heavy-duty diesel and gas vehicles (China V and above), in-use non-road mobile machinery (China IV and above), and non-local heavy-duty diesel and gas vehicles (China V and above) needed to be equipped with OBD management terminals by December 31, 2021. By the end of 2021, over 100,000 HDDVs had been registered with the Beijing Heavy-duty Diesel Vehicle On-board Emission Monitoring Platform (Fig. 3.9), effectively supporting the implementation of emission-control regulations such as the Regulations on Prevention and Control of Motor Vehicle and Non-road Mobile Machinery and ensuring air quality during major events in Beijing.

Fig. 3.9. Beijing remote OBD monitoring platform for heavy-duty vehicles



The implementation of OBD-based remote monitoring in Beijing has also promoted the development of national standards. The Limits and Measurement Methods for Emissions from Diesel-Fueled Heavy-Duty Vehicles (CHINA VI), also known as China VI for heavy-duty vehicles, formally proposed a technical mode for using remote transmission of OBD big data to monitor NO_X emissions from HDDVs. The standards specify the installation of terminals, transmission fields, transmission frequency, and require data to be transmitted to the national regulatory platform through vehicle enterprises. With the implementation of the China VI-a standard on July 1, 2021, the installation of on-board monitoring hardware became mandatory for heavy-duty vehicles. The China VI-b standard, effective on July 1, 2023, requires both the installation of OBD terminals and the uploading of collected data. The timelines for the development of OBD regulations in Beijing and China are shown in Fig. 3.10.

2017

500 heavy-duty vehicles in Beijing were retrofitted with OBD monitoring terminals

Dec 1, 2017

Local standard for OBD monitoring was released in Beijing

Jun 22, 2018

China VI standard (including OBD monitoring requirements) was released

Sep 1, 2018

OBD monitoring regulations were implemented for all newly sold and registered vehicles in Beijing

Jan, 2020

Regulations on the prevention and control of emissions from motor vehicles and non-road machinery in Beijing was released, requiring the installation of OBD monitoring terminals from May 1, 2020

May 1, 2020

Regulations on the installation of on-board terminals for remote emission management of mobile sources in Beijing (for trial implementation) was released, requiring that OBD monitoring terminals should be installed by the end of 2021

Jul 1, 2021

The China VI-a standard was implemented, requiring the installation of OBD monitoring terminals

Jul 1,2023

China VI-b standard is set to be implemented, requiring the installation of OBD monitoring terminals and the uploading of collected data.

Beijing   national

Fig. 3.10. Development of Beijing and national OBD regulations

BOX 3-1

Current situation of the international OBD

California, U.S.: The 2018 REAL project proposed the employment of sensor-based OBD data for the evaluation of CO_2 and NO_X emissions from heavy-duty vehicles since 2022 and for the inspection of emission-control systems and emission compliance since 2024. The California Air Resources Board (CARB) found that the new OBD technology can monitor vehicle emissions directly and effectively. They also indicated that the real-world emission levels of diesel vehicles are a concern. The average real-world emissions from 72 heavy-duty diesel vehicles produced after 2010 were 1.8 times the Not-To-Exceed (NTE) limit; in the case of airport buses and special-purpose vehicles, the exceedance could even be 5-10 times the NTE limit.

Europe: The Euro VI emission standard proposed the OBD-based fault and anti-tamper detection. The EU Automotive Emission Regulation Advisory Group, together with other EU and international automotive technical regulation-making organizations, recommended the introduction of OBD monitoring (called OBM in Europe) technology in the Euro 7/VII standard. OBM would be employed to monitor the actual operations and emissions throughout the lifetime and support the real-world emission regulation (i.e., regular inspections and roadside checks) for in-use vehicles.

OBD monitoring in California

I. REAL project

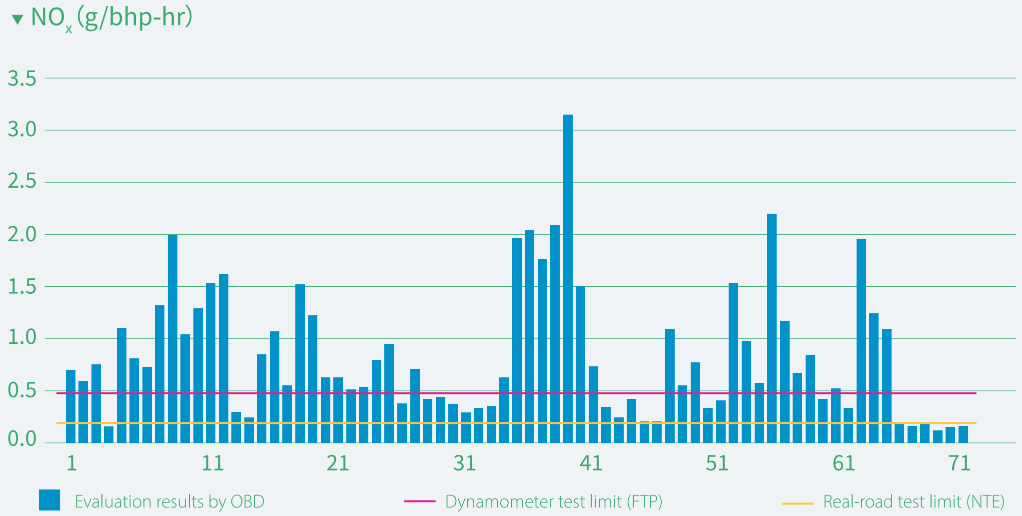
- 2008: Require OBD systems to collect HDDVs CO_2 and NO_X emissions
- 2022: Evaluate HDDVs CO_2 and NO_X emissions by OBD

II. OBD in-use emission regulation

- 2024：Conduct emission control system inspections and emission comliance by OBD

Evaluation of real-world NO_X emissions of California HDDVs based on OBD

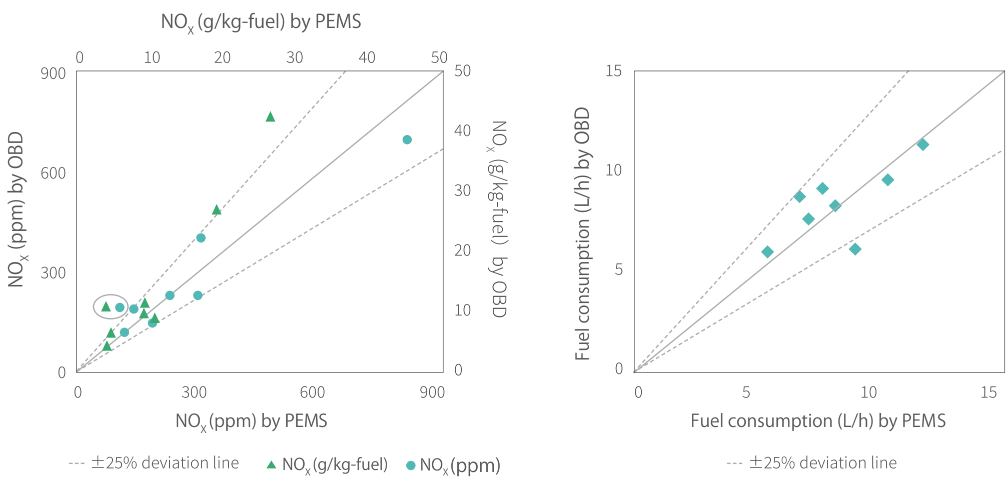
BOX Fig. 3-1 Plan for the OBD sensor data regarding emissions from heavy-duty vehicles and the assessment of real-world NO_X emissions in California, U.S.



2 Real-world NO_X emission assessment based on OBD monitoring data

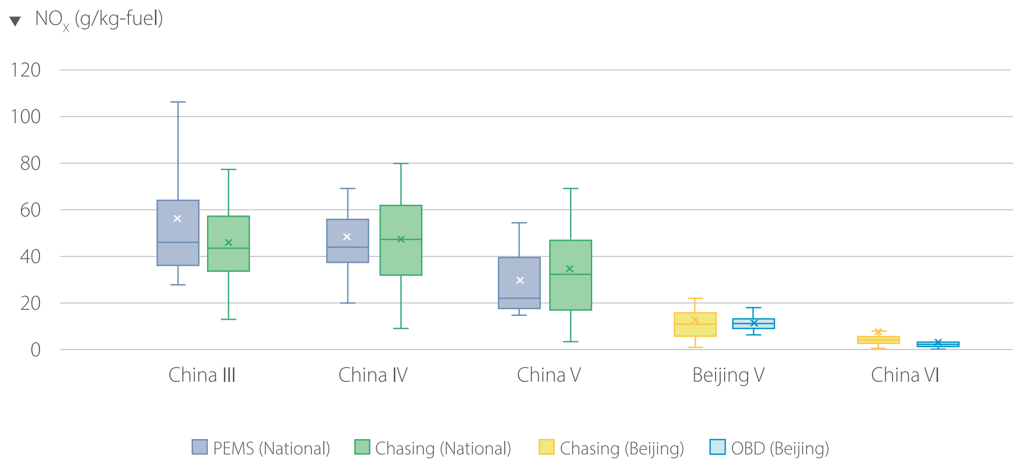
To validate the reliability of OBD, Tsinghua University developed a calibration method based on the consistency of OBD and PEMS synchronous data and found high consistency between them. The R^2 values for vehicle speed and engine speed were both above 0.95, and the average relative deviation was within ±3% for most vehicles. The correlation between second-by-second fuel flow and NO_X concentration was approximately 0.9, and the relative deviation was within ±25% (Fig. 3.11).

Fig. 3.11. Comparison between OBD and PEMS synchronous testing data



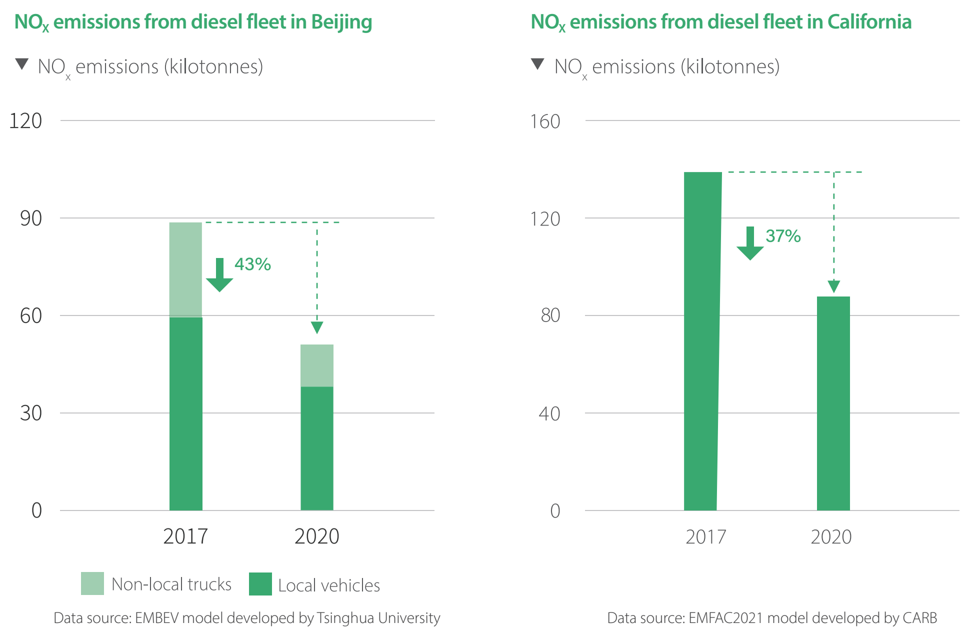
NO_X emission levels from heavy-duty fleets were evaluated based on the second-by-second OBD monitoring data and results from various testing methods (i.e., PEMS and Chasing tests). For heavy-duty vehicles in the China III-V stages, nationwide PEMS and Chasing tests were conducted, while NO_X emissions from Beijing V and China VI vehicles were mainly assessed through Chasing and remote OBD tests. As shown in Fig. 3.12, the results of PEMS and Chasing tests for China III-V vehicles were comparable, and there was also a high consistency between the Chasing and remote OBD tests for Beijing V and China VI vehicles. The real-world NO_X levels from Beijing V vehicles were 51% and 67% lower than those of China V vehicles tested by PEMS and Chasing tests, respectively. Both Chasing and remote OBD tests showed a further reduction in real-world NO_X emissions for China VI heavy-duty vehicles compared with Beijing V vehicles (i.e., approximately 32%).

Fig. 3.12. NO_x emissions from heavy-duty fleets based on PEMS, Chasing, and remote OBD tests



Strict and efficient remote OBD led to a significant reduction in NO_x emissions from heavy-duty fleets in Beijing. NO_x emissions from diesel trucks in 2020 decreased by 43% compared to those in 2017, exceeding the corresponding reduction in California between 2017 and 2020 (i.e., -37%) (Fig. 3.13). The abatement of diesel-fleet NO_x emissions also contributes to the mitigation of $PM_{2.5}$ and NO_2 pollution (especially the latter). Annual NO_2 concentrations in Beijing decreased by 37% from 2017 to 2020, meeting the requirements of air quality standards for the first time in 2019.

Fig. 3.13. NO_x-emission control benefits for diesel fleet in Beijing and California



With the advantages of high-fleet coverage, high-data accuracy, cost savings, and convenience, remote OBD is becoming a powerful and practical method for real-world emission monitoring of heavy-duty vehicles. The OBD monitoring technology will be instrumental in violation diagnosis, dynamic tracking of high-emission vehicles, monitoring of real-world fuel consumption and CO_2 emissions, and the development of high-resolution dynamic emission inventories for heavy-duty fleets. Thus, the remote OBD technology will provide significant technical support from the perspectives of emission control, air quality improvement, and CO_2 mitigation. Cities such as Beijing and Shanghai are already pioneers in implementing of remote emission monitoring for heavy-duty vehicles, and their experiences will be insightful for other cities around China and the world in achieving more accurate and efficient management of heavy-duty vehicle emissions.


source: Pixabay

04 CHAPTER

Shanghai

Promoting public-transport systems and diversifying transport energy

As China's economic and financial center, Shanghai is one of the megacities that has experienced the most prosperous development in the country. By 2020, the registered population of Shanghai had reached 24.9 million, with an average annual population growth of 2.1% over the past two decades. The GDP per capita was 157,000 CNY, with an average annual GDP growth rate of 8.6%. The scale of its built-up urban area was approximately 1.5 times larger than that in 2000. With rapid economic development and urbanization, the demand for motorized travel in Shanghai has significantly increased. However, this growth has brought about challenges such as traffic pollution, energy consumption, and congestion, which have become key bottlenecks, hindering Shanghai from achieving the status of a livable city according to international standards. In response to these challenges, policymakers in Shanghai have made substantial efforts to promote public transport systems since the 1990s, making this city a model for other Chinese cities to follow. Additionally, Shanghai has been proactive in promoting the development of new energy vehicles and experiments with the adoption of biodiesel from kitchen waste oil, aiming to continuously improve urban air quality and contribute to climate mitigation.

Fig. 4.1. Urban development picture of Shanghai

SHANGHAI

4.1

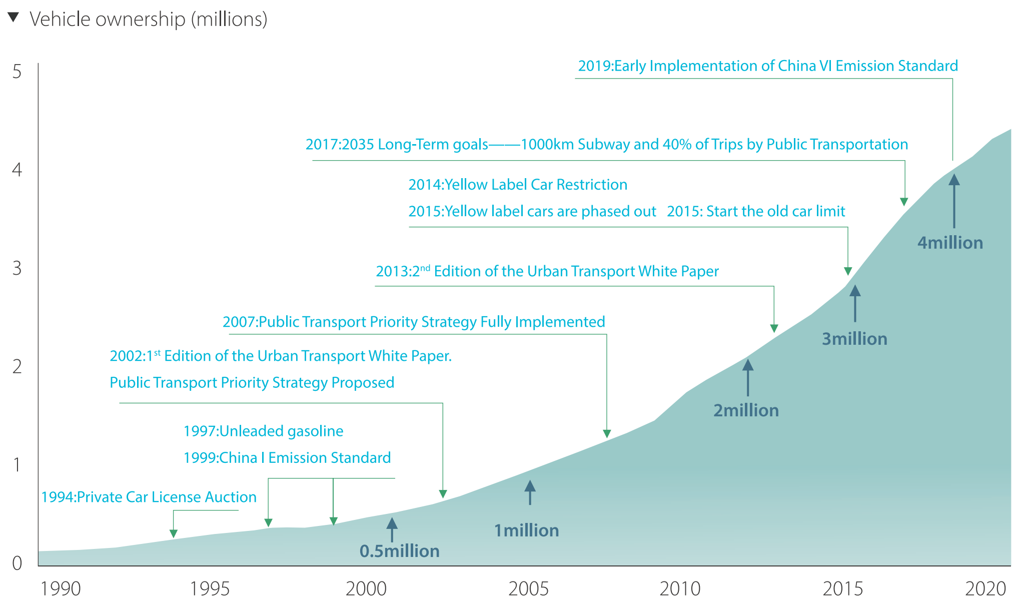
Prioritizing public-transport modes

Vehicular pollution control in Shanghai began in the 1990s, and it involved implementing a series of measures, such as banning leaded gasoline fuels, enforcing vehicle emission standards, and managing in-use vehicles. These efforts led to the establishment of an integrated management system. However, despite these initiatives, the rapid increase in car ownership still put considerable pressure on Shanghai's traffic and environmental systems. In the 1990s, the total number of on-road vehicles in Shanghai saw a remarkable annual growth rate of 12%.

To strategically address the environmental and traffic challenges brought about by rapid motorization, Shanghai took a pioneering step in 1994 by implementing an auction-based system to allocate new private car licenses for the first time. This innovative approach served as a pilot for other Chinese cities to follow, as it aimed to cap the total number of vehicles through registration control. Prioritizing public transportation became a core development strategy for meeting the travel demands of urban residents.

Since 2000, thanks to the policy promoting public transport systems, the model structure of urban transport in Shanghai has undergone significant optimization. The development of subway systems, ground public buses, and other measures effectively alleviated traffic-related environmental issues.

Fig. 4.2. Key nodes of automotive development and traffic-environment policy in Shanghai



1 History of public transport development in Shanghai

1. History of the "Prioritizing Public Transport" strategy

Since the mid-1990s, Shanghai has adopted the "Prioritizing Public Transport" strategy as a key component of its urban development. In June 2002, Shanghai issued a "White Paper On Urban Transportation", which emphasized the importance of "focusing on public transportation, supplemented by individual transportation", a pioneering message in China. This strategy ensures that capital investment, land use, and public transport operations work together to build a comprehensive system with multiple public transport modes. Rail-based transit, such as subways, serve as the backbone, while ground public buses and non-motorized transport play essential roles as well.

In 2007, the Shanghai municipal government officially implemented the "Prioritizing Public Transport" strategy and launched a 3-year action plan. This plan accelerated the construction of public transport infrastructure, such as subways and bus lanes, while optimizing public transport lines and offering transition fee discounts to encourage residents to choose public transport. As a result, the length of operational subway systems rapidly increased.

In 2013, the Shanghai municipal government issued an updated "White Paper on Shanghai Transportation Development", fully reflecting the priority of public transport in planning, investment, construction, and operation stages. While strengthening the backbone role of subway systems, Shanghai also improved ground public bus services and strengthened the connection between different transport modes. The city strictly controlled the vehicle population and encouraged a shift from private car travel to public transport through differentiated parking fees and other measures.

In 2017, the Shanghai municipal government announced its future ambition for public transport development in the "Overall Urban Development Plan (2017-2035)".The plan aims to form three "1000-km" subway networks for intercity, urban, and local lines by 2035, while also improving the "first/last kilometer" connection performance. The goal is to have public transport account for 40% of all transport modes, including non-motorized options like walking and biking.

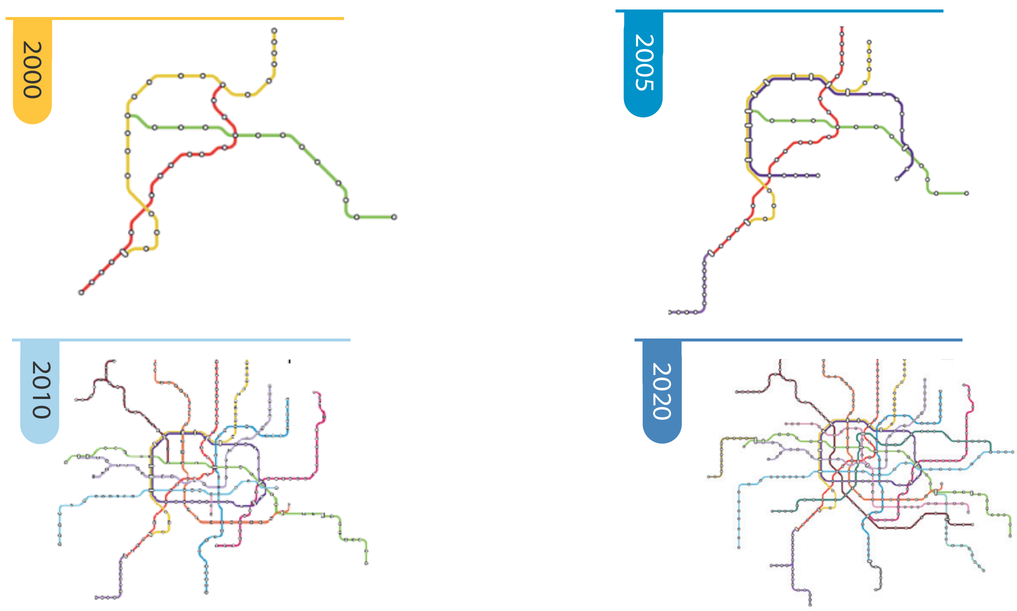
2. History of Shanghai's subway systems

Shanghai was one of the early adopters of subway construction in China. Guided by the "Prioritizing Public Transport" strategy, the city government has increased the investments in subway construction since the early 1990s. Nearly 60% of the auction income from the new license quota is allocated to subway construction annually. The first subway line in the city was completed and opened in 1993, marking a significant leap forward. By 2003, the total length of subway lines reached 109 km, surpassing Beijing as the leading city at that time.

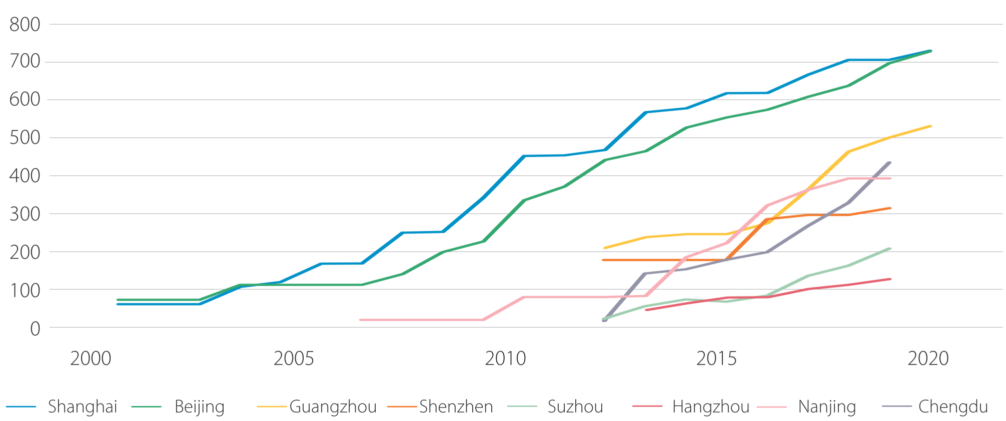
Driven by the implementation of the "Prioritizing Public Transport" strategy, the total length of subway lines in Shanghai has rapidly increased, with an annual growth rate of 15%. Resulting in a dense subway network covering almost all areas. In 2010, the operational subway lines in Shanghai reached 453 km, surpassing that of London (408 km) and ranking first worldwide. By the end of 2020, the total length of in-service subway lines in Shanghai had increased to 729 km, representing a tenfold increase compared to 2000 (Fig. 4.3).

Fig. 4.3. Comparison of the lengths of operational subway systems (primarily underground subways) between Shanghai and other major cities in China

▼ Development of the subway system in Shanghai



▼ Operating mileage of rail transit (km)



3. History of the development of ground public buses

Relying solely on subway systems is insufficient for supporting efficient and stable urban transport in Shanghai; the "two networks" of subways and ground public buses must work in tandem. Since the early 2000s, Shanghai has undertaken large-scale planning, optimization, and adjustment of the ground bus network in conjunction with subway development, commercial housing, and urban rural integration.

Shanghai has established a bus line network by combining subway network planning and public bus passenger flow corridors. It has also focused on arranging connecting lines between subway stations, bus hubs, and other public transport facilities especially in residential areas. Additionally, the city has actively promoted the construction and operation efficiency of bus-only lanes to ensure that buses maintain higher speeds than private vehicles during peak hours in congested areas.

From 2005 to 2020, the length of the ground public bus network in Shanghai has rapidly increased. By the end of 2020, the length of the bus network was 9,116 km, a 90% increase since 2005 (Table 4.1). Furthermore, the total length of bus-only lanes was 500 km, and the line network density in the central urban area was 3.3 km/km^2. The central area has achieved full coverage of bus stops within a 300-m radius, and the suburbs and new towns have a 500-m radius, providing good support for the subway network through public buses.

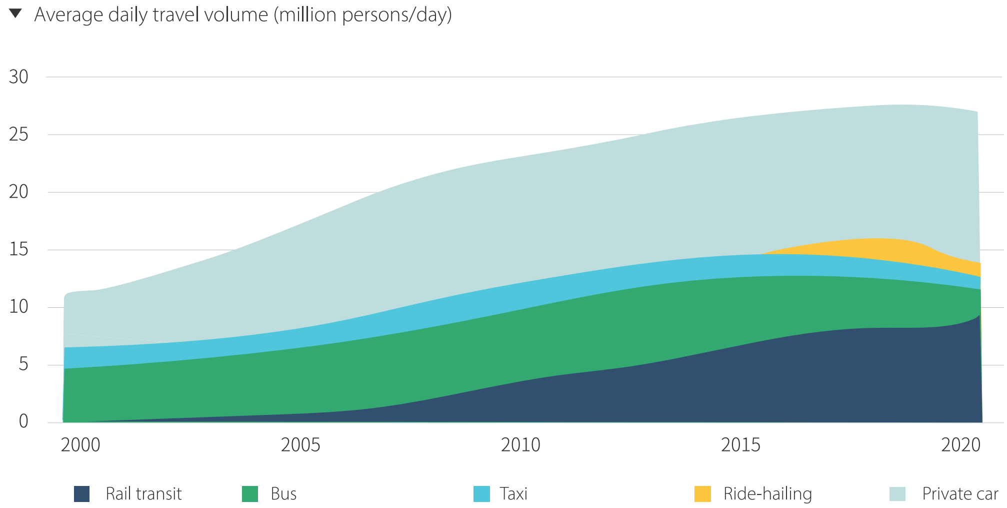
Table 4.1. Development of Shanghai public buses (2005–2020)

	Unit	2005	2010	2015	2020
Number of buses	#	17,985	17,455	16,531	17,667
Operational lane length	km	21,795	23,130	24,027	24,945
Network length	km	4,778	7,053	8,243	9,116
In which: bus-only lanes	km	20	162	312	508
Network density	km/km^2	0.8	1.1	1.3	1.4
In which: center areas	km/km^2	3.1	3.1	3.2	3.3

2 Benefit analysis for the "Prioritizing Public Transport" strategy

Since 2000, the implementation of the "Prioritizing Public Transport" strategy in Shanghai has led to a significant increase in the proportion of public transport modes and an optimized urban transport structure, despite a rapid increase in total traffic volume. In 2020, the average daily motorized travel volume in Shanghai reached 25.16 million passenger trips, marking a 133% increase since 2000 and a 15% increase since 2010 (Fig. 4.4). Among all motorized travel, the proportion of public transport has risen from 43% in 2000 to 47% in 2020. Notably, subway travel has experienced the most substantial growth, rising from 2% in 2000 to 34% in 2020, surpassing public buses and becoming a major component of public transport.

Fig. 4.4. Changes in travel volume and travel-mode composition in Shanghai from 2000 to 2020



The successful promotion of public transport has effectively curbed the growth of private vehicle travel in Shanghai. In 2020, the vehicle ownership density in the city was controlled at approximately 180 vehicles per 1,000 people, the lowest level among all developed megacities comparable to Singapore (Fig. 4.5). The rapid development of public transport has satisfactorily met residents' travel needs and reduced reliance on private vehicles. From 2000 to 2020, the traffic volume of Shanghai's subway systems increased by nearly 26.5 times, while the growth in private car travel was only 2.6 times. As shown in Fig. 4.6, in the central area with the highest density of subways and public buses (within the inner ring), the increase in automotive vehicle traffic has almost stagnated since 2010.

Fig. 4.5. Comparison of per capita GDP and vehicle ownership density in domestic and international large cities

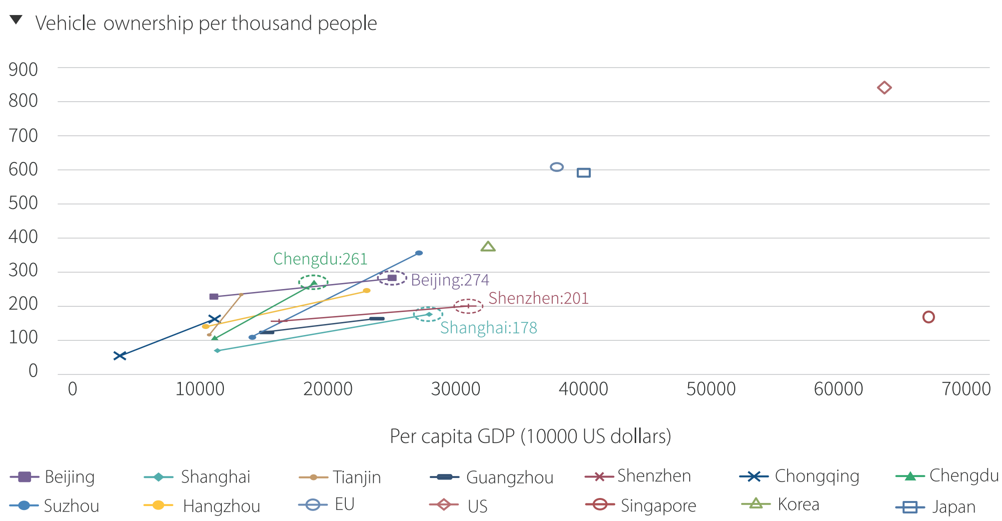
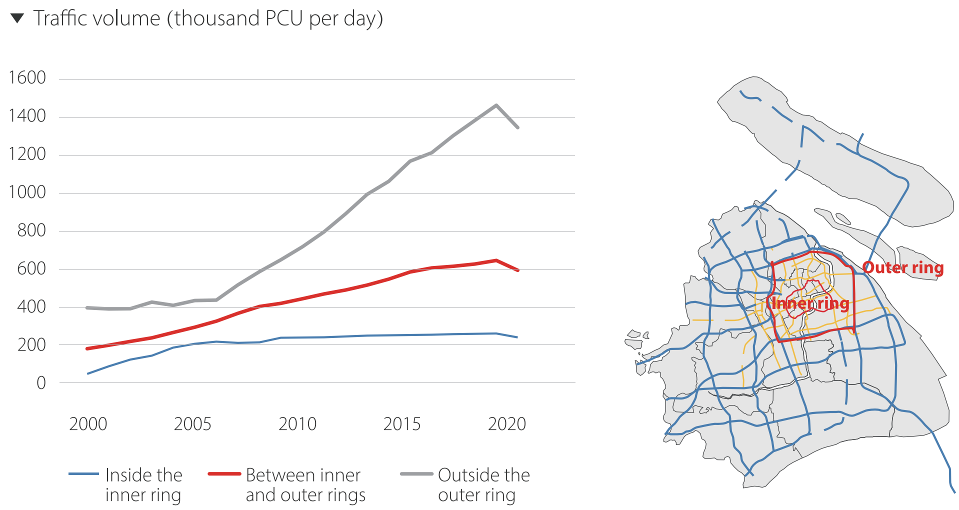


Fig. 4.6. Trends in total traffic volume in different regions of Shanghai during 2000–2020



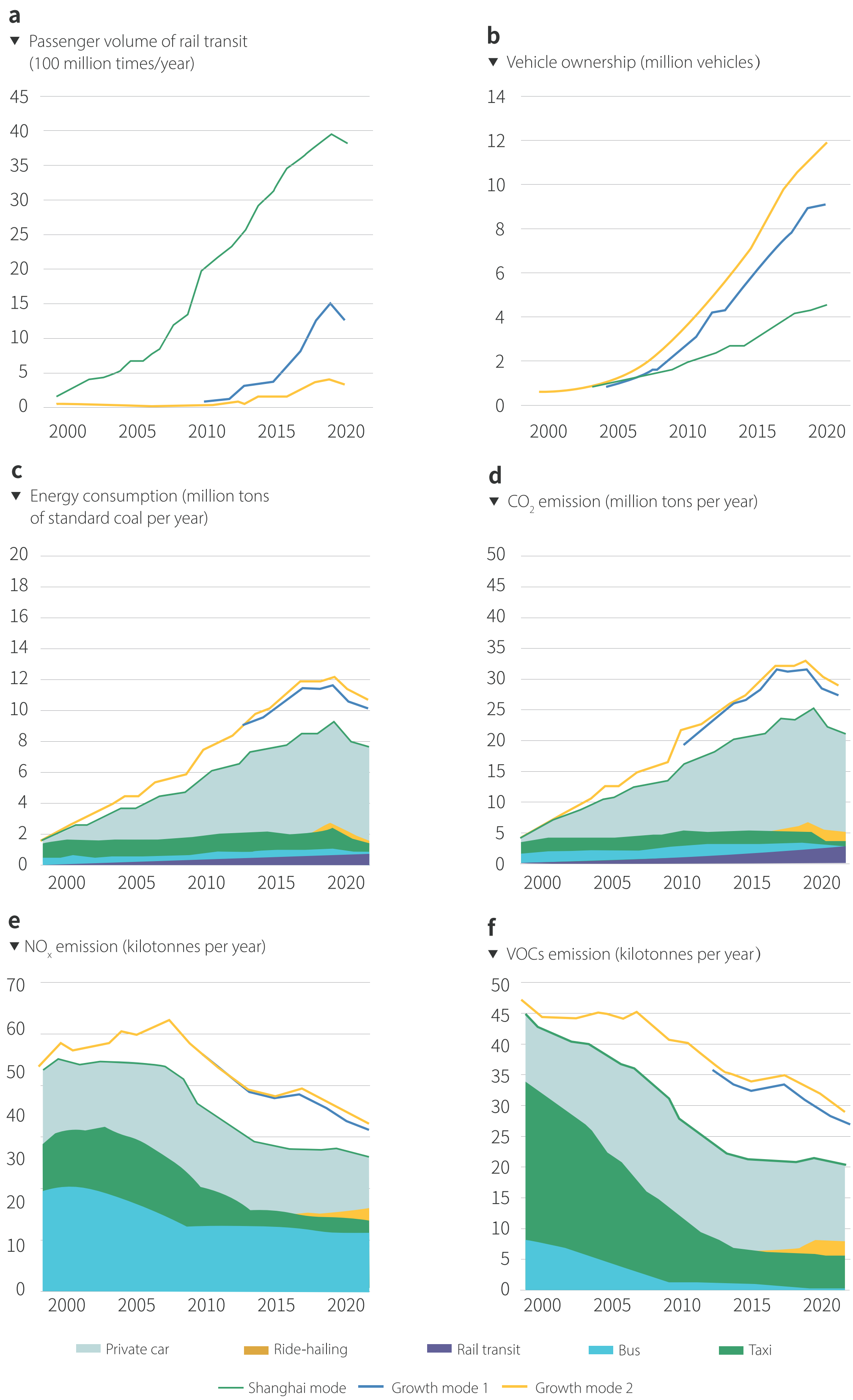
Through the implementation of the "Prioritizing Public Transport" strategy, the growth rate of vehicle ownership in Shanghai has been significantly curbed, and challenges related to urban traffic, energy, and the environment have been effectively alleviated. To assess the energy-saving and emission-reduction benefits of these measures, we compare the average (e.g., Chengdu; mode 1) and high (e.g., Suzhou; mode 2) growth rates of registered vehicles in other major Chinese cities (Fig. 4.7).

Compared to the two growth scenario modes, the development of subways in Shanghai has progressed significantly faster. As shown in Fig. 4.7 (a), the passenger traffic of Shanghai's subway systems in 2020 would be 3 and 12 times that of the "average growth" and "rapid growth" scenarios, respectively. If these scenarios had been followed, the total number of vehicles in Shanghai would have reached 8.8 and 11.6 million, or 2.0 and 2.6 times the actual level, respectively, in 2020 (Fig. 4.7 (b)).

As a result of the rapid growth of private vehicle travel, transportation energy consumption and CO_2 emissions in Shanghai also increased significantly under the two growth scenarios. In 2020, the total transportation energy consumption and CO_2 emissions in Shanghai would have increased to 7.71 and 23.16 million tonnes of coal equivalent (tce), respectively. Private passenger vehicles were the major contributors to the energy consumption growth and CO_2 emissions. As shown in Fig. 4.7 (c) and (d), under the growth scenario modes 1 and 2, the transportation energy consumption and CO_2 emissions would have increased significantly; in 2020, CO_2 emissions would have exceeded the actual level by 32% and 39%, respectively.

The effective control of private vehicle traffic has significantly reduced on-road emissions of major air pollutants in Shanghai. As shown in Fig. 4.7 (e) and (f), through implementing the "Prioritizing Public Transport" strategy and comprehensive control measures, on-road NO_X and VOC emissions in Shanghai have followed an obvious downward trend since 2008; had the "Prioritizing Public Transport" strategy not been adopted, i.e., under the two growth scenarios modes, vehicle emissions in Shanghai would have been substantially higher. In 2020, under the growth scenarios modes 1 and 2, NO_X emissions would have increased by 1.21 and 1.26 times, and VOC emissions would have increased by 1.30 and 1.38 times, respectively.

Fig. 4.7. Comparison of vehicle ownership, energy consumption, and NO_X and VOC emissions in Shanghai under different growth scenario modes



Through the implementation of the "Prioritizing Public Transport" strategy and integrated emission-control measures, NO_2 pollution in Shanghai has rapidly improved, with the central urban area showing particularly significant improvement (Fig. 4.8). Between 2015 and 2020, the NO_2 concentration decreased by 18%, with a notable reduction in high-value areas. Air quality monitoring data from traffic sites also revealed a substantial decrease in traffic-related pollutants in the central area of Shanghai since 2014. The concentrations of NO, CO, and BC changed from 81 μg/m^3, 1.1 μg/m^3, and 5.8 μg/m^3 in 2014, to 39 μg/m^3, 0.7 μg/m^3, and 2.0 μg/m^3 in 2020, decreasing by 52%, 36%, and 66%, respectively, during this period (Fig. 4.9), indicating significant progress in improving the traffic environment.

Fig. 4.8. Spatial distribution of the NO_2 concentration in Shanghai from 2015 to 2020

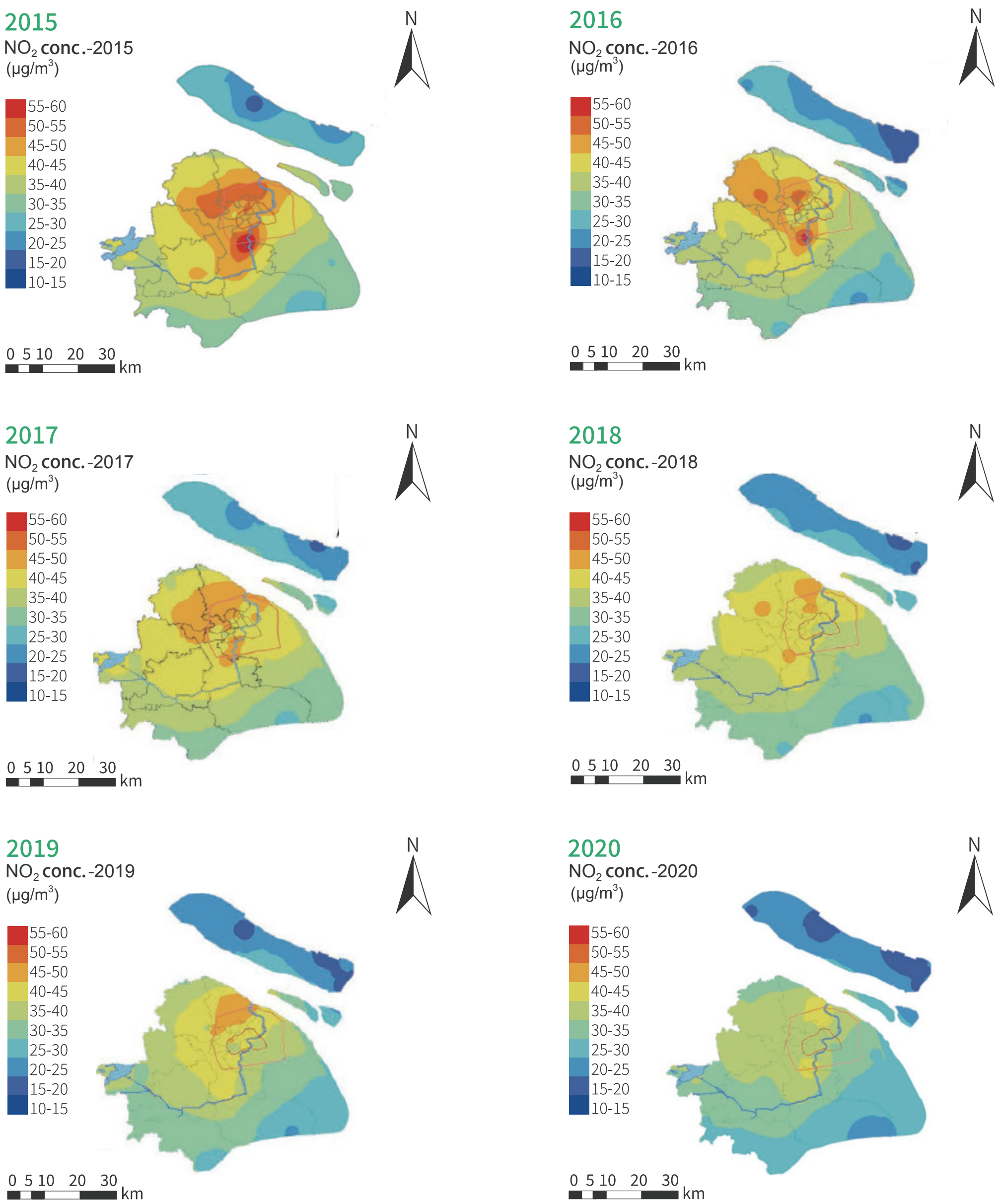
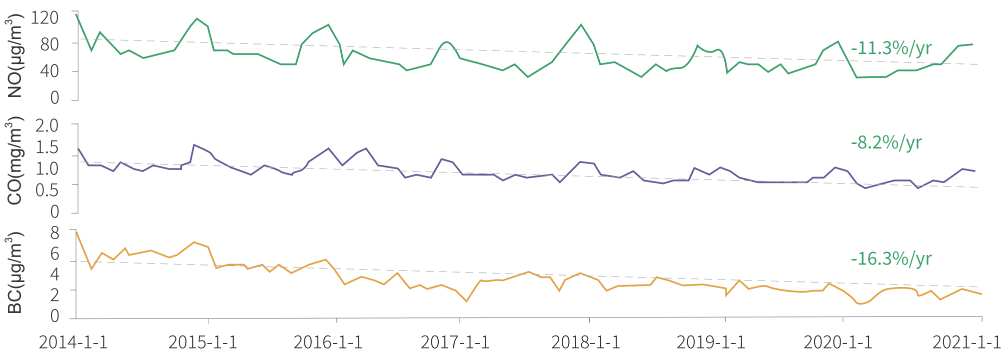


Fig. 4.9. Concentration changes of major pollutants measured at traffic sites with air quality monitoring in Shanghai



Over more than two decades, Shanghai has successfully adhered to the “Prioritizing Public Transport” strategy and gained valuable experience in controlling vehicular pollution and mitigating carbon emissions. Other cities can learn from Shanghai's approach, which involves optimizing the transport mode structure and implementing comprehensive control measures that integrate the “vehicle-fuel-traffic” systems. As a result, vehicle emissions of major air pollutants have been significantly reduced, and the growth trends in transportation energy consumption and CO_2 emissions have been effectively curbed. Furthermore, the service levels of public transport systems have improved, and traffic congestion has been alleviated. These successful experiences provide important references for decision-making regarding transport planning and pollution control in other large cities.

source: Pixabay

4.2

Promoting the diversification of transportation energy

Shanghai has been actively exploring the diversification of transportation-energy systems for more than two decades due to the significant energy consumption in the transportation sector. Since 2000, the city has been promoting the use of alternative fuels, such as liquefied petroleum gas (LPG) and natural gas (NG), for taxis and buses. Moreover, Shanghai stands out as one of the leading cities in China for adopting new energy vehicles, including plug-in electric vehicles. Starting from 2013, the number of new energy vehicles in Shanghai has grown rapidly at an annual rate of 70%. By 2020, Shanghai had a total of 424,000 new energy vehicles ranking first in the world.

Addressing concerns about waste food and preventing the reuse of waste cooking oil (commonly known as "gutter oil") in food consumption, Shanghai implemented a closed-loop governance model for the entire industrial chain, encompassing "Collection, Transport, Store, Transfer, and Application". As a significant step in this approach, the city extensively utilized biodiesel derived from waste cooking oil in buses, trucks, and other heavy-duty vehicles. This measure not only contributed to waste management but also provided valuable insights into the diversification of transportation energy sources.

1 Introduction to biodiesel

Biodiesel (BD) typically refers to fatty acid methyl esters (FAME) produced by transesterification of different animal and plant fats with methanol. The term BX denotes a biodiesel blend oil with X% BD by volume, such as B5, which is a blend of 5% biodiesel and 95% conventional diesel.

Biodiesel and its blends can be widely utilized in all types of diesel-powered vehicles and machinery. The raw materials used for biodiesel production include vegetable oils like rapeseed, soybean, and palm oils, as well as animal oils and various waste oils. Biodiesel has been employed to varying extents in Europe, the United States, Japan, and other countries and regions.

Fig. 4.10. Biodiesel and its feedstocks

2 Application of biodiesel in Shanghai

The issue of "gutter oil" poses significant challenges for policymakers in Shanghai. The improper disposal and reuse of "gutter oil" not only present major environmental and food safety concerns but also impact people's livelihoods. Shanghai produces over 30,000 tonnes of "gutter oil" annually, and due to insufficient supervision, it easily finds irregular paths, increasing the risk of contaminating food sources (Fig. 4.11).

To address this problem, Shanghai took action in 2012 by introducing the "Measures for the Treatment and Management of Waste Cooking Oil", the first local regulation of its kind in China. This initiative aimed to standardize the professional collection, transportation, transit, and primary processing of waste cooking oil. The franchise system of collection and transportation of waste cooking oil was implemented and integrated operations for collection, transportation, and processing were encouraged.

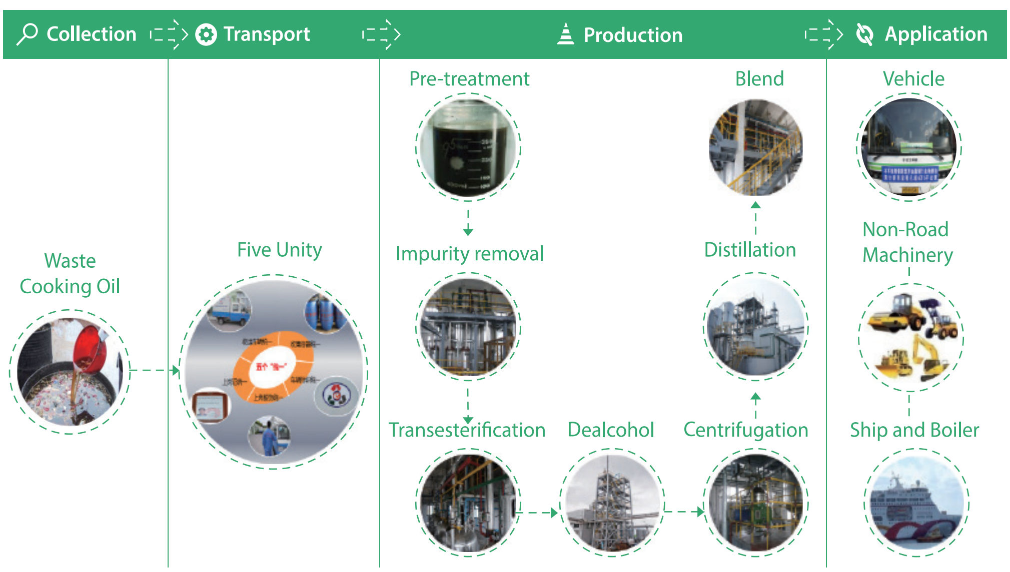
Fig. 4.11. Sources and circulation paths of "gutter oil"

In 2018, the Administrative Measures on Supporting the Promotion and Application of Bio-Diesel from Waste Cooking Oil (referred to as The Measures) were issued, further improving the closed-loop management of waste cooking oil recycling. The Measures covered collection, transportation, disposal, and promotion of waste cooking oil's application in gas stations, following a principle of "closed-loop management, market-oriented operation, and application support". Enterprises producing waste cooking oil were required to provide special containers for collection, and collection and transportation enterprises were responsible for processing the waste cooking oil into raw oil with an oil content of no less than 95%. This raw oil was then delivered to disposal enterprises to complete the closed loop of collection, transportation, and processing.

Presently, Shanghai has approximately 39,000 catering and food-processing enterprises generating waste oil. There are 18 collection and transportation enterprises, along with about 300 collection vehicles that recycle waste oil from catering enterprises daily at fixed points. To ensure better supervision of the process, an online management system for waste cooking oil was developed, and terminal video monitoring was installed at each collection and transportation unit's disposal site to enable comprehensive information-based supervision.

As a result of these efforts, the amount of waste cooking oil collected in Shanghai has significantly increased, from over 20 tonnes in 2011 to more than 200 tonnes per day. Moreover, over 50,000 tonnes of this waste cooking oil can be converted into B100 biodiesel each year, contributing to the target of collecting all waste oil in Shanghai.

Fig. 4.12. The closed-loop governance model for the whole industrial chain of "gutter oil"to biodiesel



To accelerate the application of biodiesel from waste cooking oil, Shanghai initiated in 2012 to explore its usage in vehicles. A long-term follow-up test was conducted on 20 buses using fuel mix ratios of B5 and B10 to assess the stability and reliability of biodiesel from waste cooking oil. The test results were promising, showing no soot deposition on key vehicle parts, no oil-circuit-related failures, and potential positive effects in reducing the emissions of primary particles, CO, and non-methane hydrocarbon (NMHC). These results provided a strong basis for further large-scale biodiesel applications.

Due to the higher stability and reliability of B5 diesel, Shanghai has been actively promoting its use in commercial gas stations since 2018. With the revision of the national standard for B5 Diesel (GB 25199-2017) both CNPC and Sinopec have integrated B5 diesel into their franchised fuel supply systems, making it available at approximately 300 gas stations throughout the city. To address the cost inversion challenge faced by biodiesel modulation sales enterprises caused by high collection, transport, and disposal costs, Shanghai established an emergency subsistence guarantee mechanism. This mechanism includes encouraging B5 diesel modulation sales enterprise discount promotions, providing government subsidies, and ensuring a market-based supply of B5 diesel. As a result, since June 2020, Shanghai has been supplying 1.72 million liters of B5 diesel daily to over 20,000 diesel vehicles, consuming approximately 70 tonnes of biodiesel from waste cooking oil each day.

Furthermore, Shanghai continues to conduct experimental research on the reliability and emission-reduction effects of long-term use of B10 diesel in buses, freight vehicles, ships, and industrial boilers. This research aims to further expand the application scope of biodiesel from waste cooking oil in the future. By continually exploring and advancing the use of biodiesel, Shanghai is making significant strides in sustainable transportation energy and reducing environmental impacts.

Fig. 4.13. Promotion and application of biodiesel from waste cooking oil in Shanghai

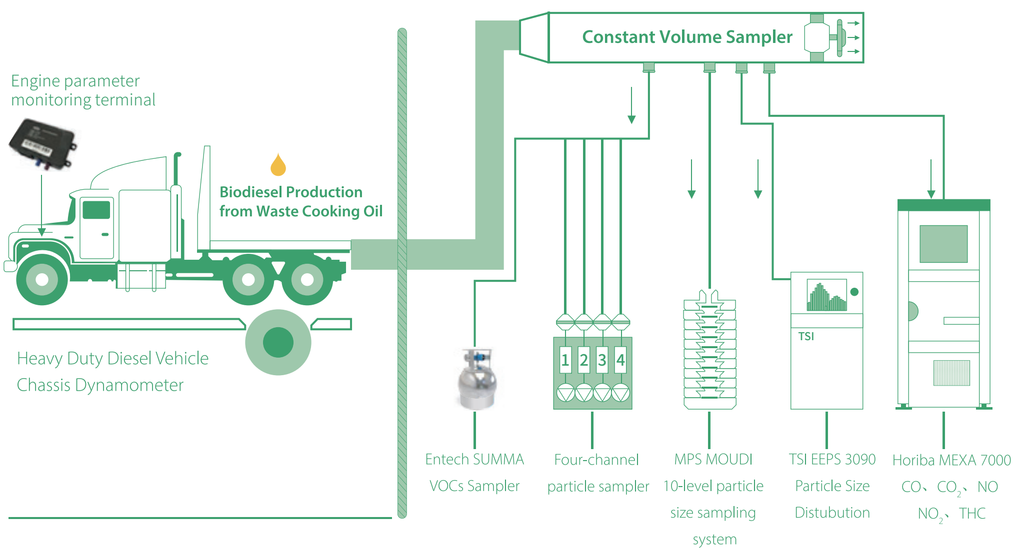
A slogan on a bus about recycling of "Gutter Oil"

Discounts on biodisel in gas stations

3 Analysis of the environmental benefits of biodiesel

To assess the environmental impact of biodiesel from waste cooking oil on mobile sources, Shanghai conducted systematic testing on the emission characteristics of HDDVs such as buses, sanitation vehicles, and freight trucks burning biodiesel with different blending ratios. Figure 4.14 illustrates the emission test system for biodiesel on a freight vehicle. The study selected ten diesel vehicles of different types, including one national III vehicle, three national IV vehicles, and six national V vehicles, using pure diesel fuel that meets the national VI standard as the baseline. Emission tests were conducted using different blending ratios of biodiesel, namely B0, B10, B20, and B50 diesel.

Fig. 4.14. Emission-test system for biodiesel blended fuel on a freight vehicle



Number	1	2	3	4	5	6	7	8	9	10
Models	Bus	Bus	Bus	Sanitation	Sanitation	Freight	Freight	Freight	Freight	Freight
Emission levels	III	IV	V	V	V	IV	V	V	IV	V
B0	√	√	√	√	√	√	√	√	√	√
B10	√	√	√	√	√	√	√	√	√	√
B20			√	√	√	√	√	√	√	√
B50						√	√	√	√	√

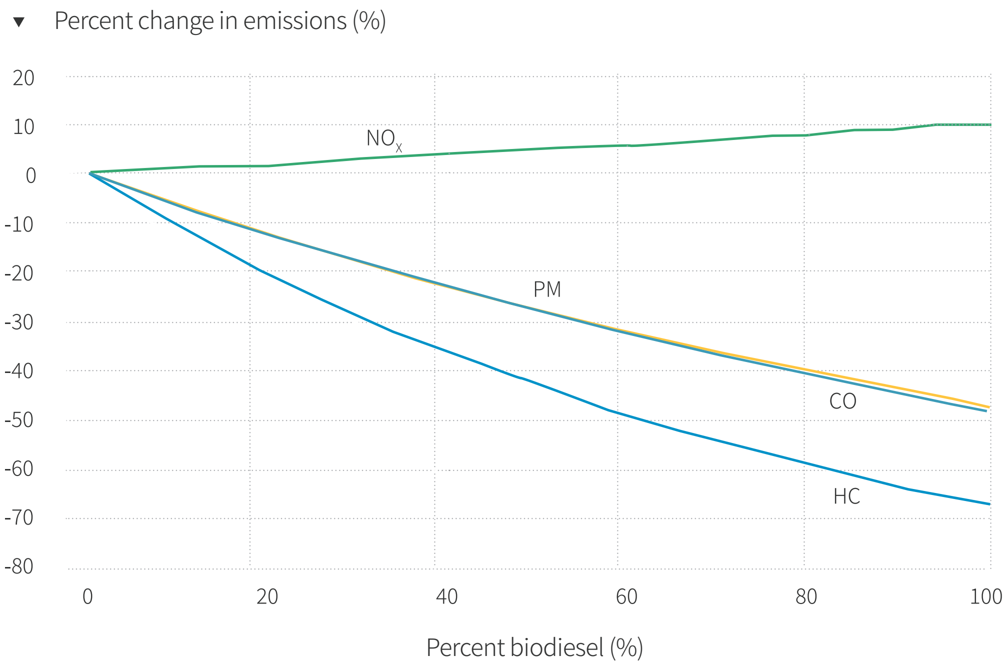
Figure 4.15 presents the results of pollutant emissions, CO_2 emissions, and fuel consumption for heavy-duty vehicles using biodiesel fuels with different blending ratios. The findings revealed that compared with B0, CO emissions decreased by 8%, 20%, and 26%, HC emissions decreased by 32%, 50%, and 60%, and particle-number (PN) emissions decreased by 17%, 34%, and 52% when using B10, B20 and B50

diesel, respectively. However, NO_x emissions showed a slight increase: NO_x emissions of B10, B20, and B50 diesel increased by 3%, 6%, and 9%, respectively, compared to B0. This is mainly due to the higher oxygen content in biodiesel, leading to higher combustion temperature and pressure than B0 diesel, which promotes thermal NO_x generation. Notably, burning biodiesel from waste cooking oil had no significant effect on fuel consumption and tailpipe CO_2 emissions from direct combustion.

Fig. 4.15. Emission-reduction effect of different blending ratios of biodiesel used by heavy-duty vehicles

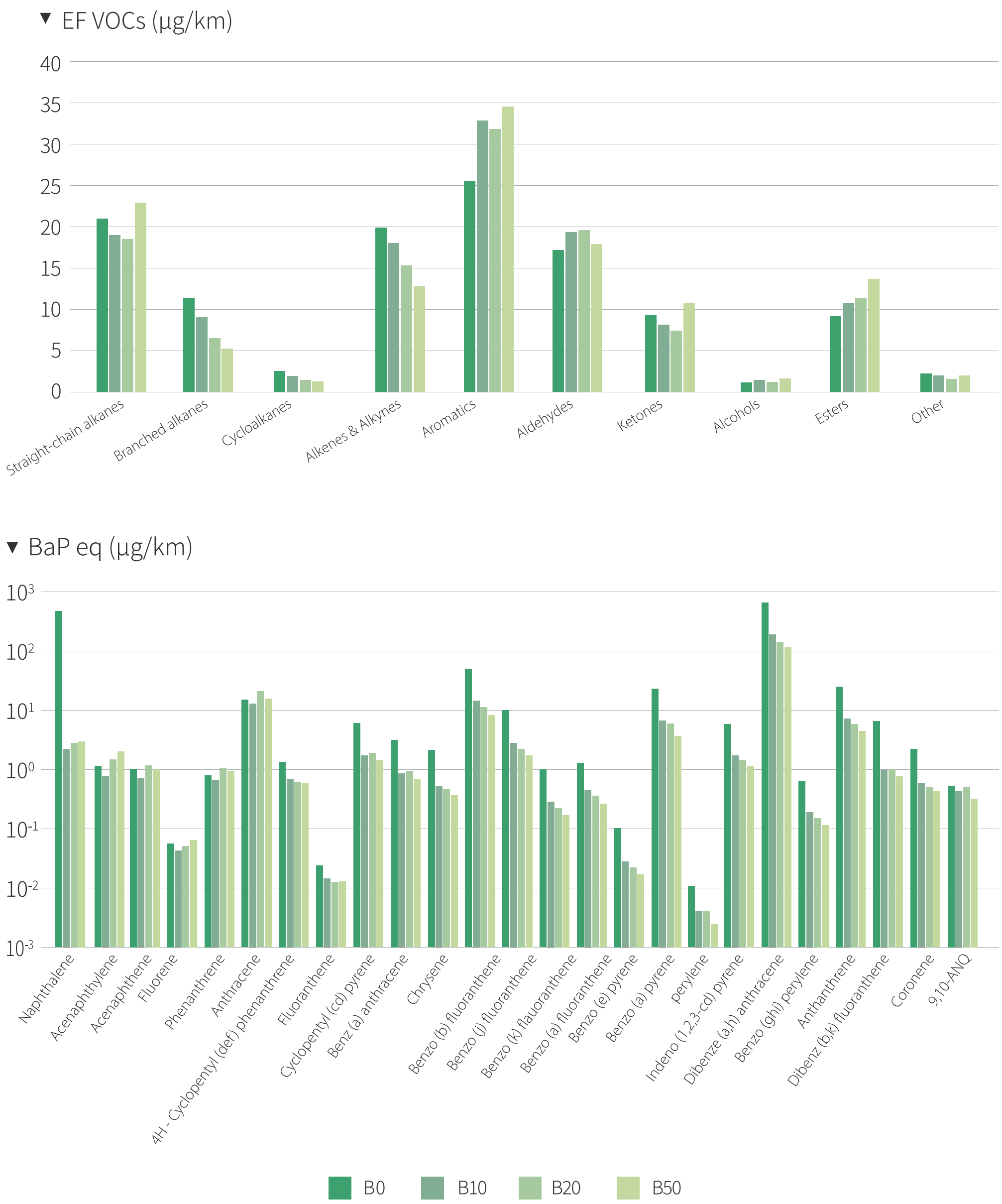
The above results (Fig. 4.15) align with existing research indicating that biodiesel can reduce the emissions of incomplete combustion products such as CO, HC, and PM, with greater reductions observed at higher blending ratios. However, NO_x emissions tend to increase, as shown in Figure 4.16. It's worth mentioning that different research results may vary in their conclusions regarding the impact of biodiesel burning on NO_x emissions. Studies on engine benches and chassis dynamometers have suggested that NO_x emissions might be slightly reduced when engine and vehicle loads are low. Moreover, with the upgrading of emission standards for diesel engines and improvements in the control accuracy of the SCR system, the increase in NO_x emissions from biodiesel can be addressed by dynamically adjusting the diesel engine injection advance angle and SCR urea injection.

Fig. 4.16. Emission-reduction effect of biodiesel mixed in different proportions (Source: US EPA , 2002)



As biodiesel contains many different types of fatty acid methyl esters and other oxygen-containing components, its combustion may result in increased in oxygen-containing organic compounds and other unconventional pollutants. As a result, unconventional pollutant emissions are a major concern, as they can lead to secondary pollution and have negative effects on human health. Figure 4.17 illustrates the emission characteristics of unconventional pollutants obtained through synchronous measurement of biodiesel burning on freight vehicles with different blending ratios. While total VOC emissions did not significantly change after biodiesel blending, there was a notable change in the chemical composition. Main diesel exhaust species, such as alkanes, alkenes, and alkynes, gradually decreased with increasing blending proportion, while aromatic hydrocarbons and oxygen-containing organic compounds, such as aldehydes, ketones, and esters, slightly increased. Some studies suggest that this is due to the formation of oxygen-containing organic matter by the breakdown of biodiesel molecules with hydroxyl and carboxyl groups. The equivalent toxicity of benzopyrene (BaP_{eq}) decreased with an increase in the biodiesel blending ratio, but the contents of low-molecular-weight PAHs, such as acenaphthylene, acenaphthylene, fluorene, phenanthrene, and anthracene, increased. Similar trends were reported by previous studies.

Fig. 4.17. Comparison of unconventional pollutant emissions from different biodiesel mixtures in freight vehicles



In addition to reduced pollutant emissions, biodiesel from waste cooking oil offers another benefit by reducing life cycle CO_2 emissions. Table 4.2 provides a comparison of CO_2 emission levels in each phase of biodiesel production from waste cooking oil with those from vegetable oil and pure diesel.

From the perspective of the raw material production process, land and fertilizer use generates CO_2 during the production of biodiesel from vegetable oil. Regarding fuel production, fossil diesel production involves the distillation and reforming of crude oil, and all types of biodiesel production require methanol, sulfuric acid, potassium hydroxide, and other raw materials, which result in CO_2 emissions. In general, biodiesel from waste cooking oil does not involve land or fertilizer use during the raw material production stage (as it is treated as reused waste) and absorbs CO_2 during the growth process. As a result, the CO_2 emissions in the entire life cycle are lower, potentially reducing the CO_2 emissions compared to the use of fossil diesel and plant-based biodiesel.

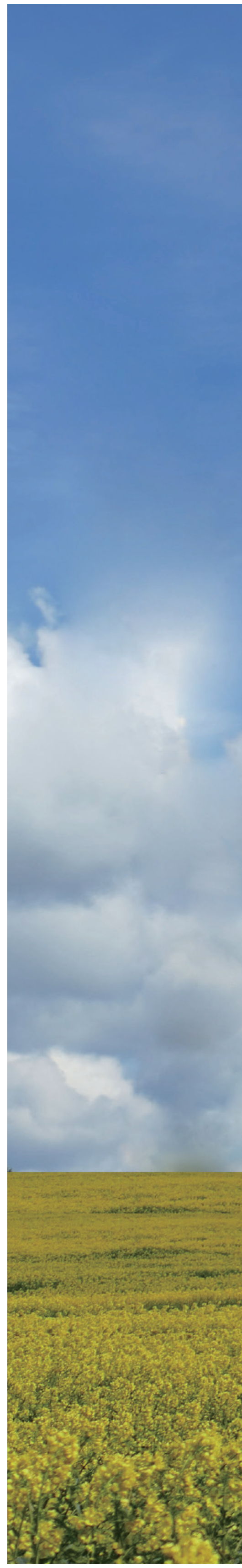


Table 4.2. Life cycle CO_2 emission levels of different types of biodiesel and pure diesel

Items		Vegetable oil to biodiesel	Waste cooking oil to biodiesel	Fossil diesel
		CO_2 emissions per unit fuel (kg CO_2/kg fuel)		
Production of raw materials	Transport and refining of petroleum	-	-	0.63
	Land use/fertilizer/N_2O emissions from plants	2.5	-	-
	CO_2 uptake by photosynthesis	-3.2	-3.2	0
Production of biodiesel	Oil/water separation (electricity)	0.010	0.010	-
	Transport (origin to factory, diesel)	0.023	0.023	-
	Esterification (electricity, coal, CH_3O, H_2SO_4, KOH)	0.41	0.41	-
	Transport (factory to gas station)	0.01	0.01	0.01
Consumption		3.3	3.3	3.2
Total		2.3	0.3	3.7

Through a decade of efforts, Shanghai has established a collective approach to promote and apply biodiesel from waste cooking oil. This approach is supported by scientific research, promoted by the government, operated by enterprises, and co-governed by society. As a result, it has not only successfully addressed food safety issues related to "gutter oil" but has also achieved excellent environmental benefits.

Assuming that Shanghai produces approximately 50,000 tonnes of B100 biodiesel from waste cooking oil annually, it can replace approximately 0.8% of diesel consumption in the transportation sector. This substitution results in a reduction of CO, THC, and PM emissions by 250-300 tonnes, 300-500 tonnes, and 50-60 tonnes, respectively. Additionally, it contributes to a reduction of about 73,000 tonnes of life cycle CO_2 emissions.

source: Pixabay

05 CHAPTER

Shenzhen

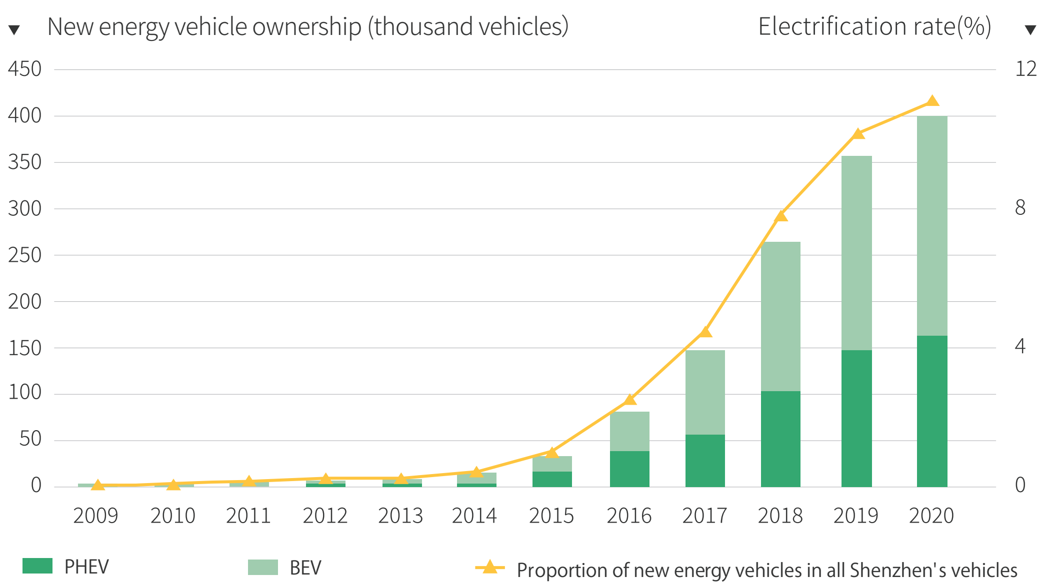
A pioneer city promoting new energy vehicles

Promoting NEVs, primarily including Battery Electric Vehicles (BEVs), Plug-in Hybrid Vehicles (PHEVs), and Fuel-Cell Vehicles (FCVs), can substantially reduce reliance on fossil fuels and mitigate greenhouse gas (GHG) and air pollutant emissions. Therefore, NEVs are considered a crucial solution for addressing the challenges of the energy crisis, climate change, and environmental pollution in the transportation sector. As a pilot city, Shenzhen has made significant efforts to successfully promote fleet electrification. By 2020, Shenzhen had approximately 400,000 NEVs on its roads (Fig. 5.1), accounting for 11% of the total vehicle population. Among all large cities in China, Shenzhen has led the transition to NEVs and has consistently been recognized as one of the "EV Capitals" by the International Council of Clean Transportation (ICCT). Additionally, Shenzhen has built a complete industrial chain and supplementary systems to ensure the continuous development of NEVs. The city is home to over 2,000 NEV-related enterprises, making it one of the world's most prominent hubs for NEV industries. A robust NEV industrial ecosystem has emerged, with major vehicle manufacturers forming strong business relationships with local suppliers and infrastructure stakeholders (e.g., charging facility companies).

The promotion of NEVs not only forms a core part of Shenzhen's local clean air action plan called "Shenzhen Blue" (Fig. 5.2) but also plays a vital role in driving a low-carbon transformation of the city's energy and industry systems. With these impressive achievements, Shenzhen has undoubtedly become a pioneer city in the global promotion of NEVs.

Fig. 5.2. Beautiful cityscape under the "Shenzhen Blue" action plan for clean air

Fig. 5.1. Growth in the total number of NEVs in Shenzhen during 2009-2020



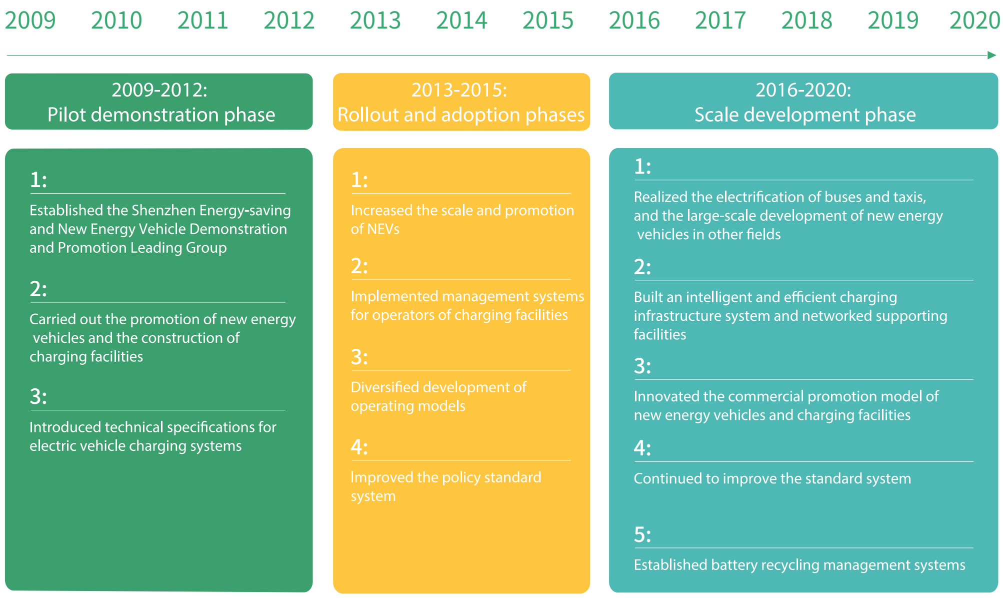
5.1

The history of promoting NEVs in Shenzhen

Since being selected as one of the demonstration cities during the "Ten Cities, Thousand New Energy Vehicles" program in 2009, Shenzhen has implemented a series of policies and regulations to promote NEVs. Over 30 standards and administrative rules directly related to NEVs were issued, covering areas such as development planning, financial subsidies, infrastructure development, market supervision, industrial access, technological innovation, battery management, and vehicle purchase quotas. By the end of 2020, the number of NEVs in Shenzhen had reached approximately 400,000, boasting the highest electrification rate among cities in China (Fig. 5.1). Currently, bus and taxi fleets are fully electrified, and the deployment of charging facilities is world leading. These remarkable achievements in the promotion of NEVs are an impressive representation of the "Shenzhen Speed".

The process of promoting NEVs in Shenzhen can be divided into three phases (Fig. 5.3), the first phase was the pilot period from 2009 to 2012, the second phase was the rollout and application period from 2013 to 2015, and the third phase was the large-scale development stage from 2016 to 2020.

Fig. 5.3. Development phases of new energy vehicles (NEVs) in Shenzhen during 2009–2020



To meet the requirements for demonstrating and promoting NEVs, Shenzhen issued the "Implementation plan for demonstration and promotion of energy-saving and NEVs in Shenzhen (2009-2012)" in 2009. This plan focused on demonstrating of NEVs in three major areas: public fleets, official vehicles, and private cars. The Shenzhen government also proposed the construction of supporting charging facilities and offered subsidies. During this phase, Shenzhen placed great importance on promoting NEVs among the public. For instance, during the 2011 Shenzhen Universiade, the government engaged with local manufacturers (e.g., Wuzhoulong, BYD) and successfully promoted thousands of electric buses and taxis.

From 2013 to 2015, Shenzhen built on the experience from the previous stage and implemented subsidy measures to provide stronger policy incentives. During this period, the number of NEVs promoted in Shenzhen ranked among the highest in China. Shenzhen also tested various business models to encourage the development of electric vehicles. In the field of private vehicles, use patterns, such as car rental, time-sharing, and multi-person sharing of electric vehicles were investigated. For commercial vehicles, leasing options for electric buses, taxis, and logistics vehicles were adopted, thereby rapidly increasing the proportion of NEVs in public fleets.

Bus companies are encouraged to explore a variety of operating options based on their features. For example, the Shenzhen Bus Group signed a purchase contract with manufacturers that included a maintenance service package for electric buses. The company also signed another agreement with charging infrastructure operators, who would be responsible for the construction of charging stations and charging services. Meanwhile, the Shenzhen Eastern Bus Company and Shenzhen Western Bus Company purchased major vehicle bodies through financing, while the main powertrain components (i.e., batteries, electric motors, electronic control systems, and charging equipment) were leased from suppliers. This approach minimized the initial investment while ensuring the quality of operation and maintenance of electric vehicles.

To accelerate the promotion of electric taxis, Shenzhen issued the "Implementation Plan of New Energy Taxi Promotion" in 2015. Taxi companies were required to allocate 10%-15% of the quota for electric models based on their evaluation scores, and an extra 5%-30% quota of new electric taxis would be given to the companies as a reward based on the replacement pace of internal combustion engine vehicles. These electric taxi quotas were exempted from usage fees for a 5-year validity period, and each taxi could obtain 80,000-136,000 CNY of purchase and use subsidies. With the dual benefits of vehicle quotas and economic subsidies, Shenzhen promoted more than 1,500 electric taxis in 2015.

A comprehensive management system, including regulations and standards, has been developed to effectively support the development of NEVs. Twenty-four municipal-level standards and administrative rules have been issued and implemented, covering NEV maintenance, construction and operation of charging infrastructure, battery management, and more. This has created a favorable environment with systematic standards and positive policy encouragement for the widespread adoption of NEVs.

Since 2016, Shenzhen has explored the application of new technologies and operating models, introducing a series of new policies to encourage the large-scale development of NEVs. Notably, the complete electrification of taxi and bus fleets (Fig. 5.4) has been achieved, and the scale of fleet electrification among commercial vehicles, such as urban logistics vehicles, commuter shuttles, and sanitation vehicles, ranks among the top in the world.

Fig. 5.4. Shenzhen Bus Group, the world's largest electric bus operator

Regarding charging infrastructure, Shenzhen has mandated that newly built communities develop parking spaces with charging stations at a ratio of 30%, and existing residential areas and social public parking lots should be equipped with charging stations at a ratio of 10%. The government has encouraged social capital to participate in the construction of charging facilities, laying a solid foundation for the rapid development of electric vehicles in Shenzhen. In summary, the government plays an important role in guiding the direction, while financial institutions are introduced to implement the leasing system, which stimulates the vitality of the market. Additionally, utility companies and other relevant sectors are encouraged to participate, further contributing to economic benefits.

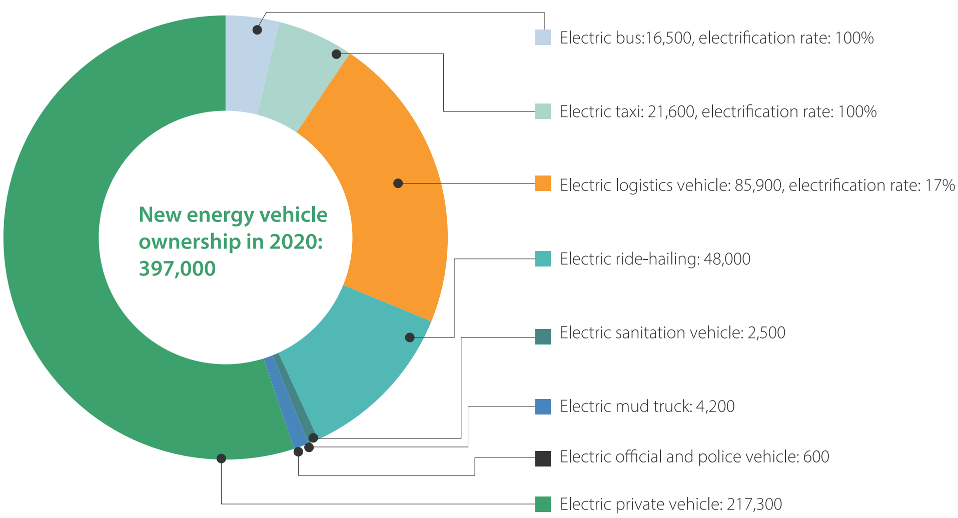
Shenzhen has continued to improve its standard automotive battery systems. This includes establishing a testing and certification system for operating vehicles and automotive batteries, an information management system for power batteries, and a cascade utilization and recycling industry system for power batteries, all of which guarantee the healthy development of NEVs.

After more than 10 years of effort, Shenzhen has achieved fruitful results in the promotion of NEVs. The number of NEVs in the city increased rapidly from 530 in 2009 to 397,000 in 2020, with an average annual growth rate of 82.5%. NEVs now account for 11% of the total ownership of vehicles, and the electrification rate is the highest among large cities in China (Table 5.1). Shenzhen has made substantial progress in electrification of public and commercial fleets (Fig. 5.5). In 2017, Shenzhen became the first city in the world to achieve 100% electrification of buses, and by the end of 2018, the taxi fleet was fully electrified, becoming the largest electric taxi fleet in the world. Finally, the number of electric trucks has ranked the highest all over the world during the past five years.

Table 5.1 Ownership of NEVs in megacities in China in 2020

City	Ownership of NEVs (thousand)	Ownership of total vehicles (million)	Electrification rate (%)
Beijing	412	6.57	6.3
Shanghai	424	4.69	9.0
Guangzhou	269	3.08	8.7
Shenzhen	397	3.59	11.1

Fig. 5.5. Composition of NEVs promoted in Shenzhen in 2020

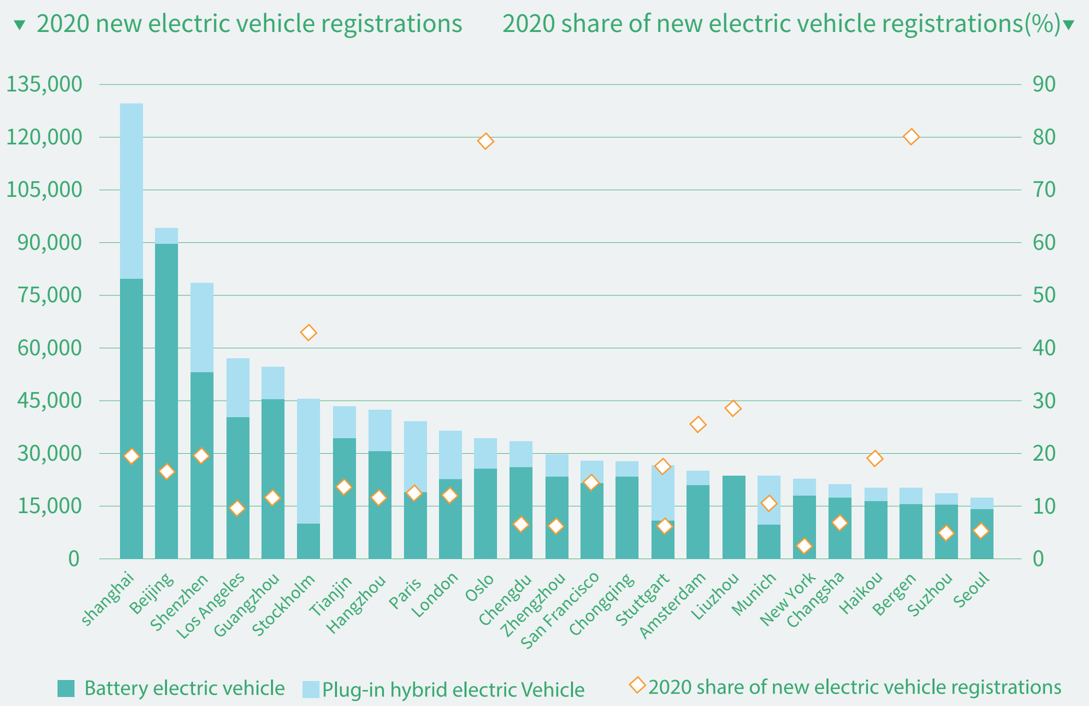


BOX 5-1

EV capitals recognized by the International Council on Clean Transportation (ICCT)

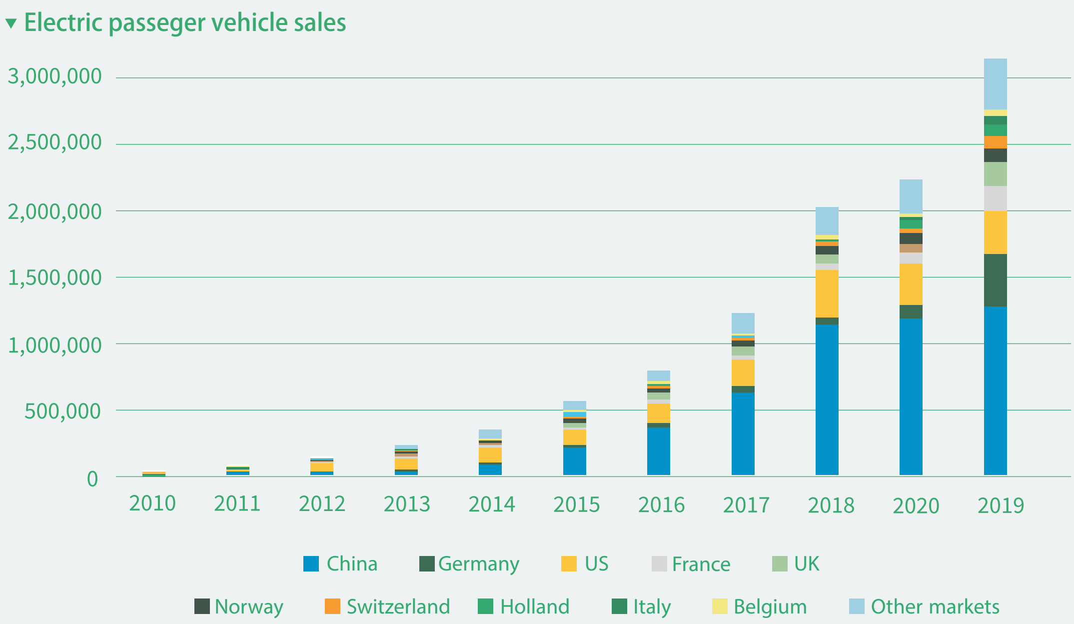
Cities play a key leading role in accelerating the vehicle electrification. Since 2017, the ICCT has selected 25 cities as "Electric Vehicle Capitals", leading the promotion of passenger vehicles. In 2020, cities from nine countries were on the list, including 13 in China, 8 in Europe, 3 in the United States, and Seoul in South Korea (BOX Fig. 5-1). These 25 cities consist of only 4% of the world's population, but electric passenger-vehicle sales are as high as 32% of the world's total.

BOX Fig. 5-1 Number of registered electric passenger vehicles and share of electric passenger vehicle registrations for the 25 electric vehicle capitals in 2020.



At the national market level, China's annual sales of electric passenger vehicles was 1.3 million units in 2020 with an increase of 8.7% over 2019, accounting for 41% of the global market, and the annual sales of electric passenger vehicles have led the world for six consecutive years. Germany, the United States, and France, ranking 2nd, 3rd, and 4th, had annual sales of 1/3, 1/4, and 1/7 of that of China, respectively. The European market is making outstanding progress. The annual sales of electric passenger vehicles amounted to 1.4 million units in 2020 with an increase of 143% over 2019.

BOX Fig. 5-2 Global electric passenger vehicle sales by market from 2010 to 2020

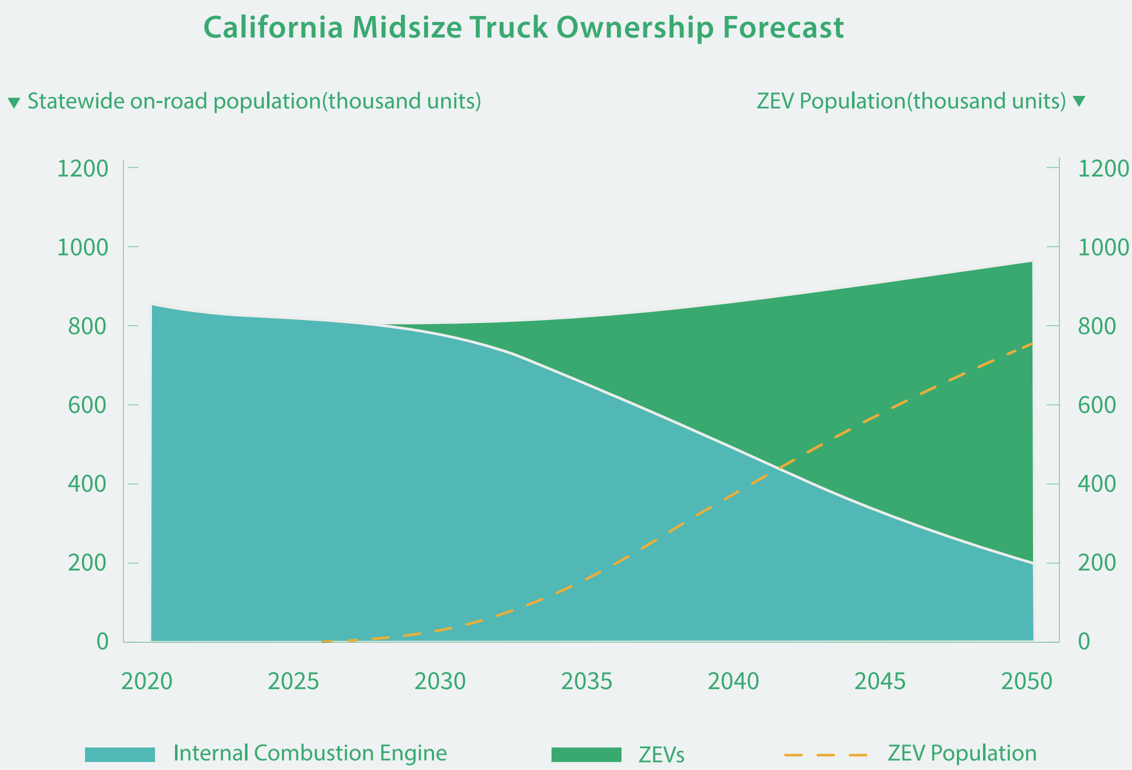


BOX 5-2

California zero-emission truck regulations

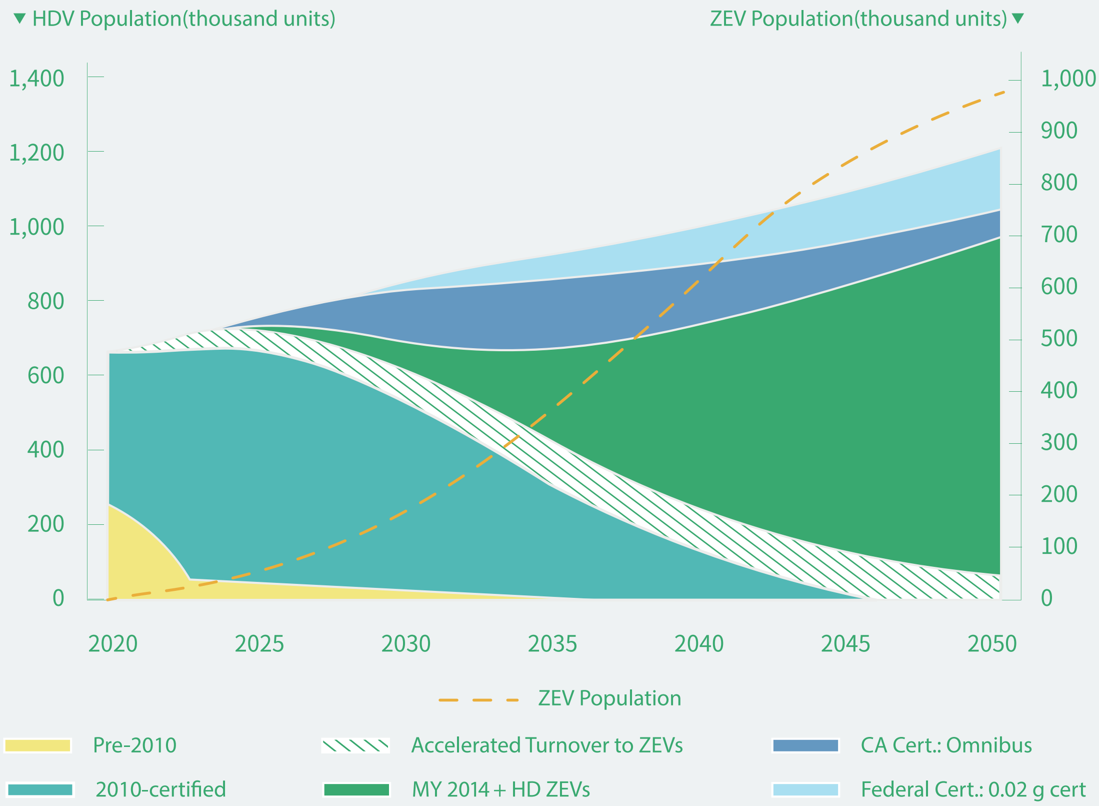
The California Air Resources Board (CARB) has been studying and developing zero-emission vehicle (ZEV) regulations for trucks since 2016. After four years of investigation and research, the Advanced Clean Trucks Regulation was officially adopted in June 2020. This is the first mandatory zero-emission truck regulation in the world. For the class 2b-8 (i.e., 4.5 tonnes or more) trucks, a

BOX Fig. 5-3 Truck ownership and zero-emission vehicle-share forecast in California, 2020–2050.



certain marketshare of zero-emission vehicle is required from 2024 onward, and by 2045 all-new trucks on sales will be converted to zero-emission vehicles. It is expected that by 2050, 80% of the heavy-duty trucks in California will be zero-emission vehicles (BOX Fig.5-3). The introduction of this regulation will significantly accelerate the new-energy and zero-emission transformation of the truck market, having far-reaching historical significance on a global level.

2020-2050 California Heavy-duty Truck Ownership Forecast

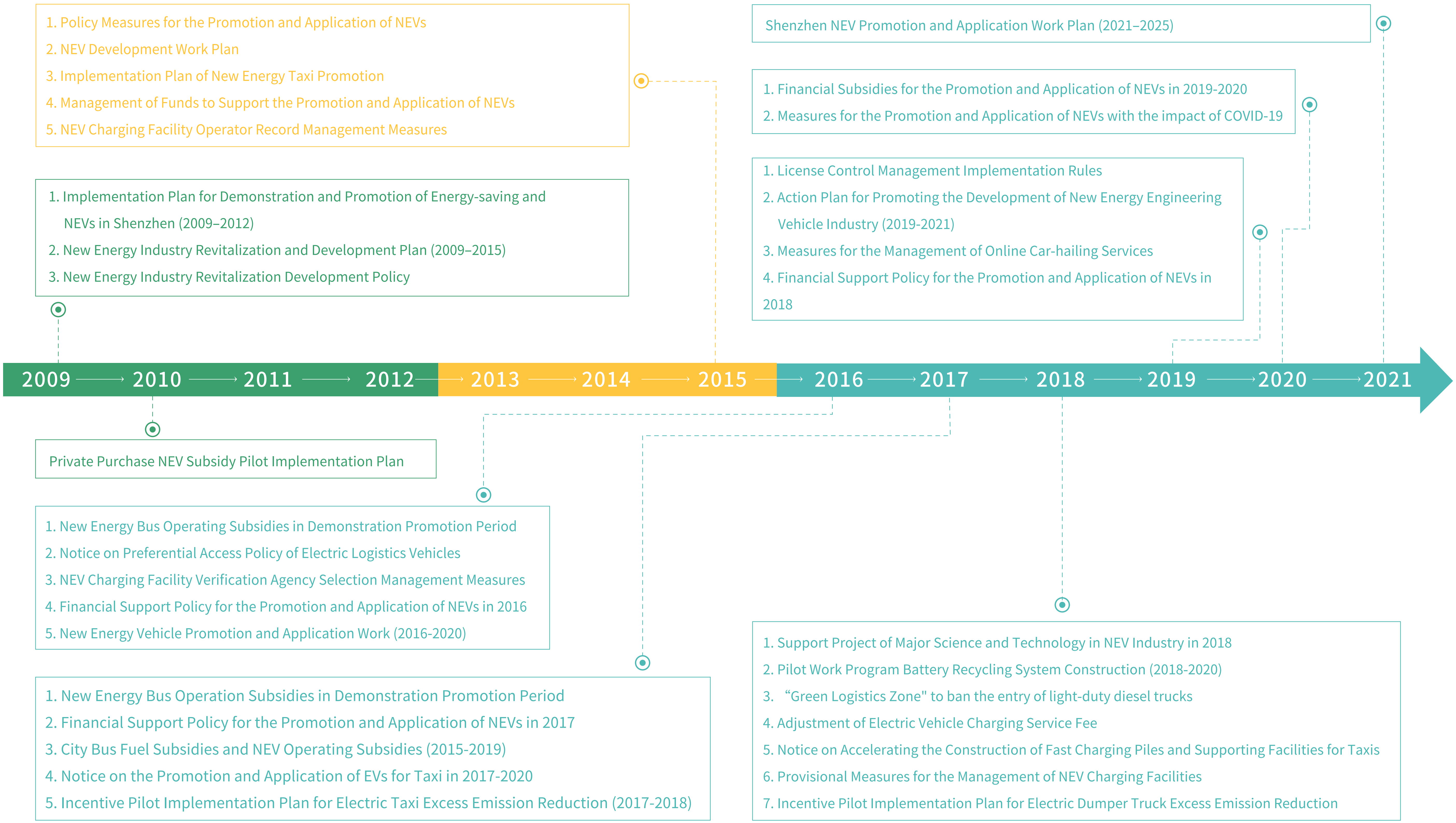


5.2

Development of policies and supporting systems for the promotion of NEVs

Shenzhen, developed a general plan and implemented measures to support the NEV industry. Owing to the cooperation between the government and market, a comprehensive support system was established, with the focus being on gaining valuable experience in NEV promotion. From 2009 to 2021, more than 30 standards and administrative rules directly related to NEVs were issued (Fig. 5.6), with the standards covering development planning, financial subsidies, charging infrastructure, market supervision, industrial access, technological innovation, battery management, and purchase quotas. In addition, the revised and issued technical specifications related to NEVs covered the aspects of charging systems, vehicle maintenance, and the construction of charging facilities. These efforts have improved the construction of a standard system for the NEV industry. In this report, we have discussed economic subsidies, industrial and infrastructure support, and green logistics zones in detail.

Fig. 5.6. NEV promotion policies in Shenzhen, 2009-2021



1 Comprehensive life cycle subsidy and incentive policies

Diversified subsidies and incentive measures have played a crucial role in the rapid development of NEVs in Shenzhen. The Shenzhen government has introduced several economic incentives for NEVs throughout their life cycle. These subsidies include purchase subsidies (financial incentives for NEV purchases), reduced fuel costs (charging cost subsidies), support for charging infrastructure (charging pile construction subsidies), and end-of-life incentives (power battery recycling subsidies), creating a comprehensive system to attract new NEV users.

Shenzhen provides subsidies for the purchase and operation of commercial vehicles, including buses, taxis, logistics vehicles, and dump trucks. Private vehicle owners are encouraged to buy NEVs through purchase subsidies and reduced or waived purchase taxes. Additionally, NEVs are granted priority registration under license control management. Aligned with national incentives, Shenzhen has introduced effective municipal fiscal policies from 2015 to 2020, including purchase subsidies from January 1, 2013, to June 30, 2021. The subsidies were based on the battery mileage under the reference test cycle, with electric cars purchased from 2013 to 2015 receiving 35,000-60,000 CNY. In 2020, the purchase subsidy was reduced to 20,000 CNY per vehicle due to declining battery costs. The government also adjusted the original purchase quota limit to 20,000 vehicles per year in 2019, with the quotas of newly registered PHEVs and BEVs subject to approval after a qualification review process.

In terms of charging and parking costs, Shenzhen provides various incentives to NEV users, including charging subsidies, lower electricity prices, and reduced parking fees. Charging subsidies are issued to NEV purchasers in the form of charging discount cards after vehicle registration. Since July 2018, the upper limit of the charging service fee in Shenzhen has been reduced from 1.0 CNY/kWh to 0.8 CNY/kWh to reduce charging costs. NEVs are exempt from short-term parking fees in roadside parking spaces for the first hour per day and in government-managed parking facilities for the first two hours per day.

Furthermore, the city encourages private investment and supports the development of charging infrastructure by offering subsidies to charging facilities that meet the standards, based on their installation capacity. Additionally, NEV manufacturers are responsible for battery recycling, with special funds allocated for battery recycling treatment at a standard amount of 20 CNY/kWh, and local finance providing subsidies of up to 50% of the audited amount of funds.

2 Development of a comprehensive NEVs industry chain

During the early promotion stage, Shenzhen attached great importance to the long-term development of its NEV industry. The promotion of NEVs was considered as an entry point for transforming the city's energy structure and industrial layout. In 2009, the "Shenzhen New Energy Industry Revitalization and Development Plan (2009~2015)," was released, serving as an effective strategy for developing the NEV industry. A few years later, the municipal government issued the "Shenzhen New Energy Automobile Industry Base Comprehensive Development Plan", which laid a solid foundation for the city to develop a mature ecosystem in the NEV industrial chain.

After years of development, Shenzhen has gathered more than 2,000 NEV-related enterprises, making it one of the cities with the highest density of NEV enterprises in the world. As a result, a perfect industrial chain has been developed in the city, which is composed of major NEV manufacturers (e.g., Build Your Dreams - BYD) and supplemented by manufacturers of power batteries and raw materials (e.g., BAK batteries and Xing Yuan materials), drive motors (e.g., Dadihe), electronic control systems (e.g., Xinwanda and Huichuan Technology), and charging infrastructure (e.g., Aotexun and KSTAR). This industrial ecosystem supports the healthy development of vehicle manufacturers and their cooperation with suppliers and infrastructure stakeholders.

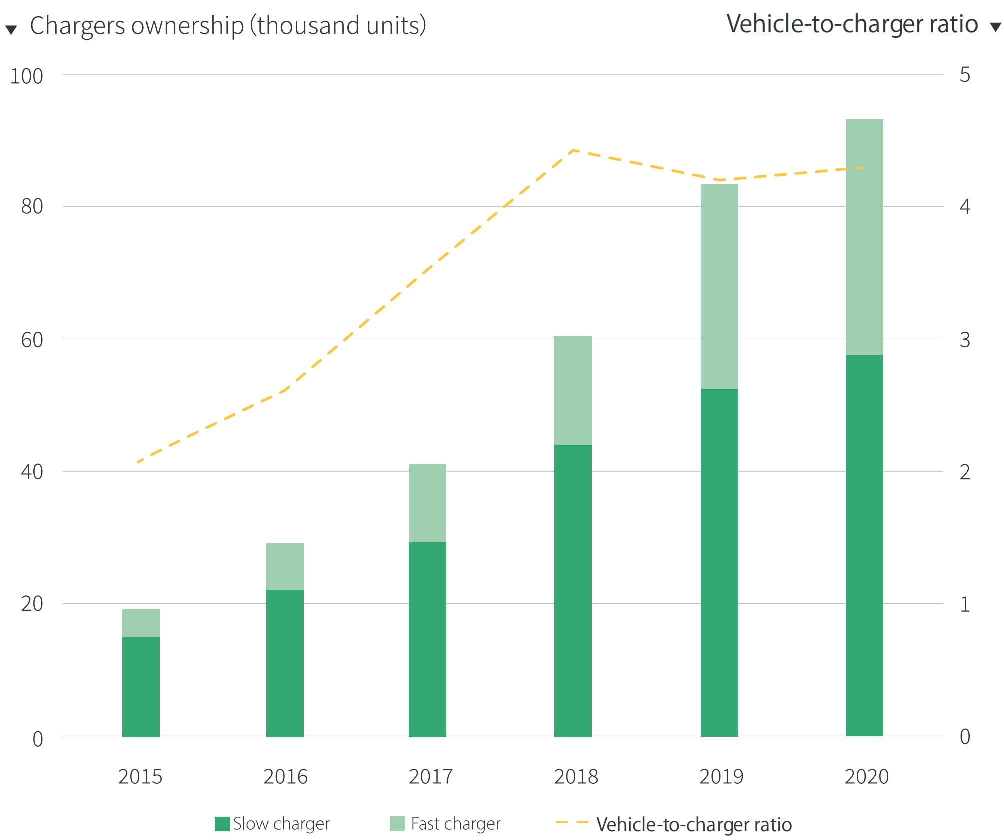
3 Construction of charging infrastructure

In the process of promoting charging infrastructure, Shenzhen used a diversified pattern to guide innovative service models, while the government promoted land use and provided strong financial support. This attracted social funds, facilitated construction, and accelerated the pace of commercialization of the charging facility network in the city. In addition, Shenzhen issued a series of standards for charging technologies, stations, piles, and facility operators, which have standardized the investment, construction, and operation of charging facilities in the city.

Shenzhen has implemented targeted measures to address the charging needs for different usage scenarios. For example, to deal with the inconvenience of charging the battery in electric taxis, three major models were promoted to improve the utilization efficiency of public resources. The first model is a "smart parking plus charging pile," which uses roadside parking resources and consists of building roadside charging piles; this model solves the problem of insufficient charging facilities. The second model is a "transformer substation plus charging station," which consists of building charging stations around the substation that tap the land and power supply potential for constructing charging stations. The third model was "parking lot plus charging pile," which utilized the original parking lot space for charging pile construction. Electric sanitation vehicles rely on public facilities for charging, however, there are only a limited number of charging facilities for sanitation. Therefore, special strategies were developed to promote the supporting work of charging piles for electric sanitation vehicles. Additionally, the Shenzhen government encouraged all districts to adopt concepts of "sharing and new construction" and "centralized and decentralized" to support the promotion of special charging piles for sanitation vehicles. To construct charging facilities for private vehicles, the Shenzhen government stipulates that new residential and large public buildings and social public parking lots should reserve 30% parking spaces for slow-charging piles (with 100% possible conditions) to ensure future construction and installation.

With the rapid construction of charging facilities, the number of charging piles in Shenzhen has increased significantly in recent years (Fig 5.7). By the end of 2020, the city had built 93,000 public charging piles of various types, with a vehicle-to-pile ratio of 4.3:1. This value is significantly better than the national average (6.1:1), with Shanghai and Beijing having ratios of 5.0:1 and 5.1:1, respectively.

Fig 5.7. Ownership of vehicle chargers and the vehicle-to-charger ratios in Shenzhen during 2015–2020



During the 14th Five-Year Plan (2021-2025), Shenzhen will continue to improve its charging infrastructure to accommodate more NEVs. According to the "Shenzhen NEV Promotion and Application Work Plan (2021-2025)," which was released in 2021, the city will build 43,000 public and private fast chargers, and 724,000 basic slow chargers by 2025. In the field of public services, Shenzhen has promised to accelerate the improvement of the integrated guaranteed system for the operation, parking, and charging of NEVs (e.g., public transportation and logistics) to achieve an average service radius of less than 0.9 km for urban charging. The city is also committed to realizing the interconnection of the charging infrastructure on intercity highways.

4 New practice of "green logistics zones"

Light-duty diesel trucks are widely used in urban logistics, primarily for short-distance transportation within urban areas. In 2017, these trucks accounted for 5.5% of the total number of motor vehicles in Shenzhen; however, their $PM_{2.5}$ and NO_X emissions accounted for nearly 20% of the total vehicle emissions. Therefore, the negative air quality impacts from urban logistics cannot be overlooked.

To improve traffic conditions and reduce pollutant emissions from light-duty diesel trucks, Shenzhen took the lead in setting up "green logistics zones" in 2018 to demonstrate the use of new energy logistics vehicles. The green logistics zones were selected based on areas with high traffic emissions, using local traffic emission monitoring data. Shenzhen established 10 green logistics zones in 10 administrative jurisdictions.

Since July 2018, the green logistics zones have banned the entry of light-duty diesel trucks throughout the day, allowing only electric trucks to pass. Violators of the notice are fined 300 CNY and penalized with three points on their driver's license (note: in China, a driver's license is suspended if over 12 points are recorded). The design of the green logistics zones provides a privilege for electric logistics vehicles, which solves the dilemma of electric logistics vehicles having no access advantages and low operational efficiency. Thus, it plays a positive role in the promotion and use of new energy logistics vehicles in Shenzhen. By the end of 2020, Shenzhen had 86,000 electric light-duty trucks, which represents an increase of 91% when compared to 2017. The proportion of NEVs in the light-duty truck fleet was 22%.


source: Pixabay

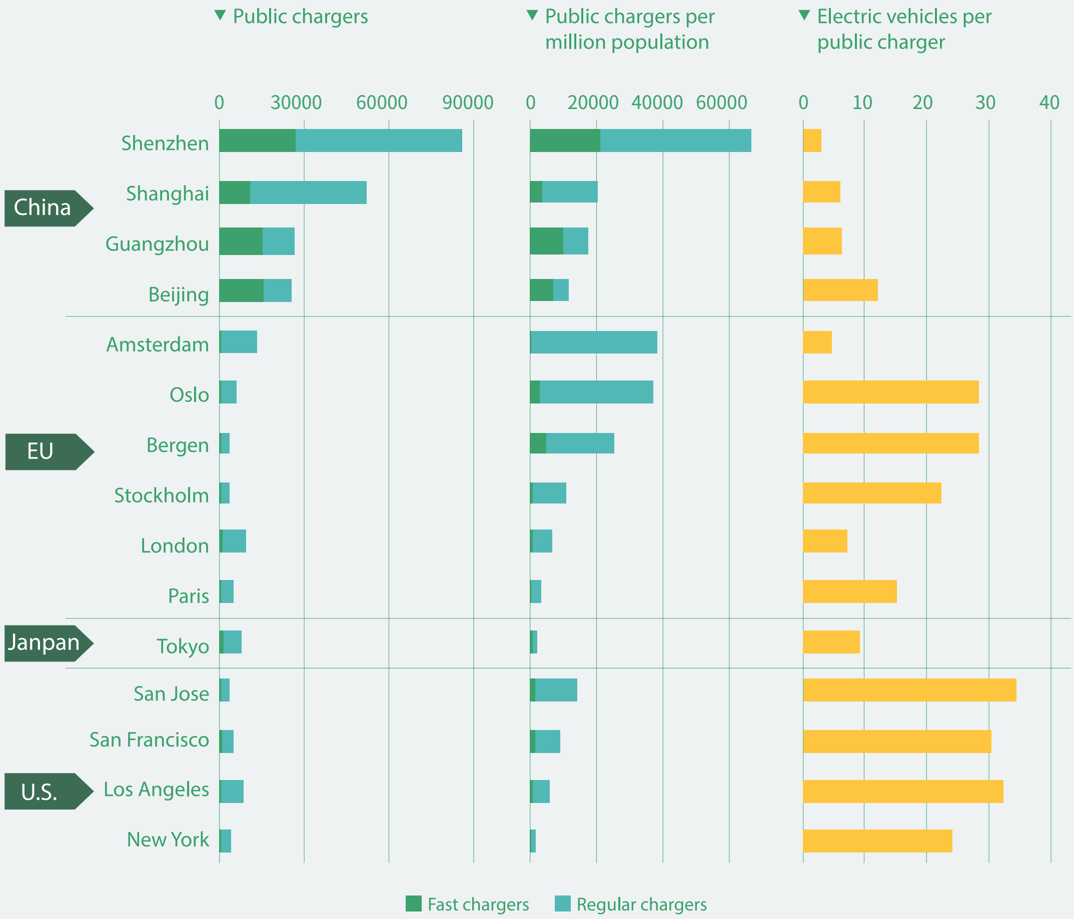
BOX 5-3

Construction of charging infrastructure in major cities in the world

The ICCT compares the construction of public charging infrastructure in some of the world's important electric vehicle capitals, including the numbers of public charging piles, public charging piles per million population, and electric passenger vehicles corresponding to each public charging pile (BOX Fig. 5-4).

In cities in China, the number of public charging piles is high, with the number in the four cities in the figure being more than twice that of the cities in Europe, Japan, and the United States of America (USA). In terms of the ownership of public charging piles, Shenzhen has obvious advantages. The number of public charging piles per million population in Shenzhen is more than 6,700, and the number is close to 4,000 in Amsterdam and Oslo. The number of public charging piles per million population in other cities in the figure is less than 2,500. From the perspective of the vehicle-to-pile ratio, Shenzhen, Shanghai, Guangzhou, Amsterdam, London, and Tokyo have a vehicle-to-pile ratio of 10:1 or lower, while the vehicle-to-pile ratio of Oslo, Bergen, and California cities is 25:1 or higher. Notably, in this study, we did not count private charging piles, which is the main reason for the low vehicle-to-pile ratio in the European and American cities. The optimal vehicle-to-pile ratio in the city also depends on comprehensive factors, such as the number of private household charging piles in the city and the use mode of the vehicle.

BOX Fig. 5-4. Development of public charging infrastructure in selected EV capitals in 2019



5.3

Promotion benefits of NEVs

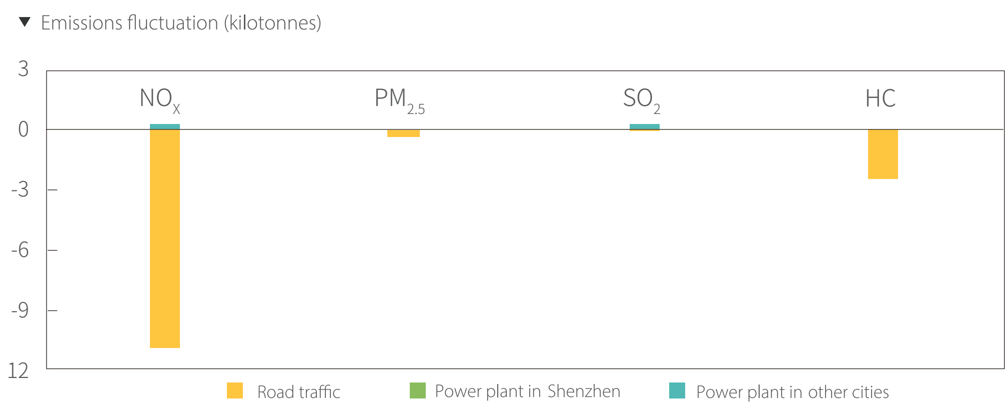
To evaluate the comprehensive benefits of promoting NEVs in Shenzhen, Tsinghua University evaluated the benefits of NEVs, including emissions reduction, air quality improvement, and health benefits. The assessment was largely based on localized databases and a life cycle perspective. The life-cycle assessment model adopted the framework of the GREET2018. Air quality simulations were carried out using the regional-scale air quality model system (CMAQ/2D-VBS) and a high-resolution dispersion model (AERMOD/RapidAir) to evaluate air quality improvements for the entire city and within traffic-dense areas. The aim of the assessment is to: 1) evaluate the environmental benefits of promoting of existing electric vehicles in Shenzhen in 2019 and 2) predict the development scenario of electric vehicles in 2030 and evaluate the environmental and health benefits of future fleet electrification.

1 Benefit assessment of current NEVs promotion

By the end of 2019, Shenzhen achieved complete electrification of taxis and buses; the total number of promoted electric trucks was close to 80,000, and the proportion of electric vehicles for medium-duty and light-duty trucks was 40% and 20%, respectively. The total number of light-duty passenger BEVs and PHEVs was more than 210,000, and the number of heavy-duty passenger vehicles was more than 4,000.

By 2019, the promotion of NEVs reduced emissions of 11,000 tonnes of NO_X, 2,400 tonnes of HC, and 300 tonnes of $PM_{2.5}$. Meanwhile, the promotion of electric vehicles increased the electricity demand in Shenzhen. Since power plants are generally equipped with ultra-low emission control technologies, and 75% of Shenzhen's electricity supply is from outside the region, electrification has a limited impact on the city's emissions from power plants (Fig 5.8).

Fig. 5.8. Changes in emissions due to the promotion of NEVs in Shenzhen between road traffic and power plants



As shown in Fig 5.9, taxis, passenger cars, and light-duty trucks are the three fleets that contribute the most to HC reductions, with contributions of 51%, 29%, and 9%, respectively. Buses contributed the most to NO_X and $PM_{2.5}$ reductions (57% and 61%, respectively). Heavy-duty passenger vehicles , medium- and light-duty trucks contributed 14%, 12%, and 8% to the total NO_X reductions, and 12%, 8%, and 9% to $PM_{2.5}$ reductions, respectively.

Fig.5.9. Contribution of electrification of Shenzhen fleets to the reduction of pollutant emissions in 2019

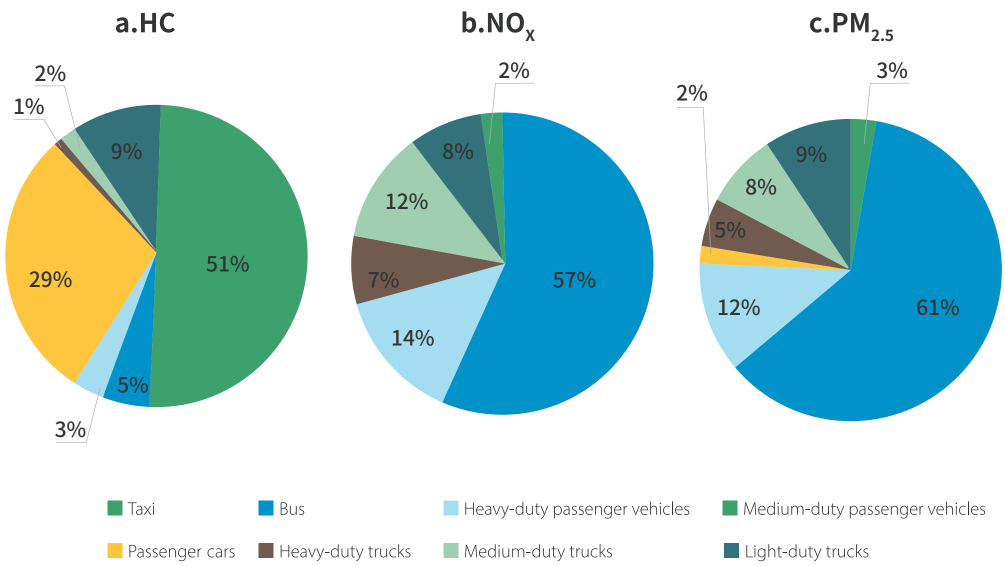
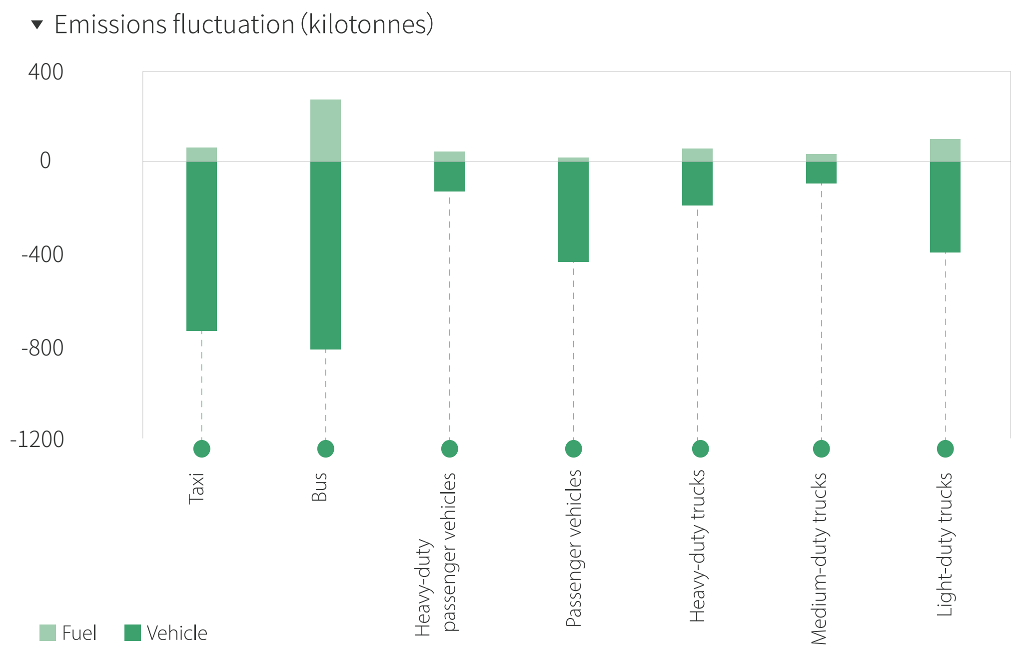


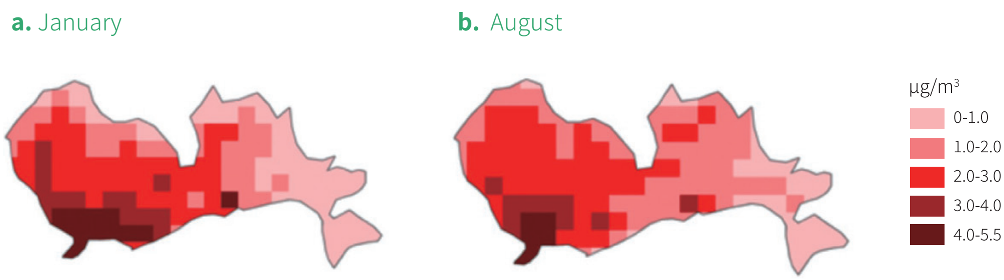
Fig 5.10 portrays the benefits of electrification in reducing greenhouse gas (GHG) emissions during the fuel cycle. In 2019, the promotion of NEVs in Shenzhen resulted in a 2.16 million-tonne reduction in GHG emissions, almost all of which was from CO_2 reduction. Taxis and buses contributed the most to this reduction (680,000 tonnes and 540,000 tonnes, respectively).

Fig.5.10. Impact of promotion of NEVs in on GHG emissions in Shenzhen in 2019



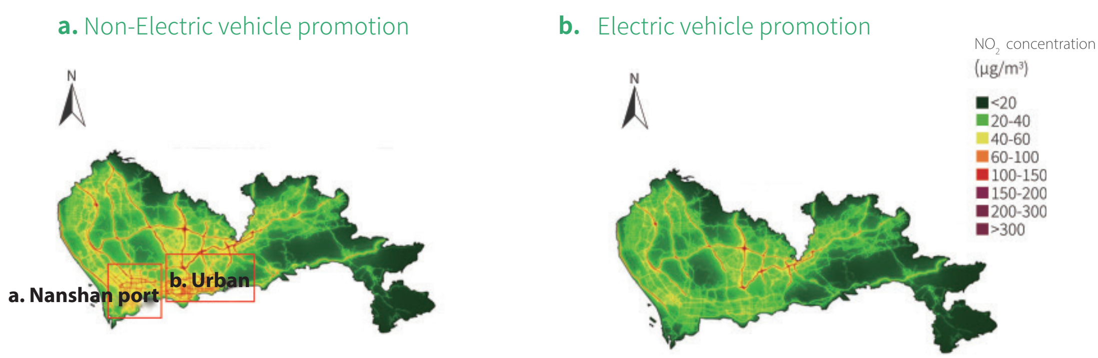
Based on the changes in emissions, a multilayer air quality model system was applied to further the evaluate benefits of electrification in Shenzhen regarding to air quality improvement (Fig 5.11). EVs reduced the average monthly concentration of NO_2 in Shenzhen by 2.8 µg/m^3 in January and 2.6 µg/m^3 in August 2019. The concentration reductions were more pronounced in urban areas (Futian, Nanshan, and Luohu districts), where reductions could be as high as 3.5-4.1 µg/m^3. Combined with the monitoring data of state air-sampling sites, the average NO_2 concentration in Shenzhen was reduced by approximately 8 µg/m^3 in 2019 compared to 2014. It is estimated that 35% of the reduction in NO_2 concentration could be attributed to fleet electrification in recent years.

Fig.5.11. Spatiotemporal distribution of NO_2 concentration reduction benefits of electrification in Shenzhen



To further explore the concentration patterns in traffic-dense areas, the high-resolution RapidAir model was used to simulate the NO_X concentrations. In 2019, NEV promotion reduced the daily average concentration of NO_X by approximately 4.5 µg/m^3. For urban and port areas with heavy traffic flows, the improvements in air quality were more significant; the average daily NO_X concentration in road traffic was reduced by 22 µg/m^3 in urban areas and 15 µg/m^3 in the Nanshan port (Fig 5.12).

Fig. 5.12. Comparison of NOx concentrations for the scenarios of electrification or non-electrification in Shenzhen




source: Pixabay

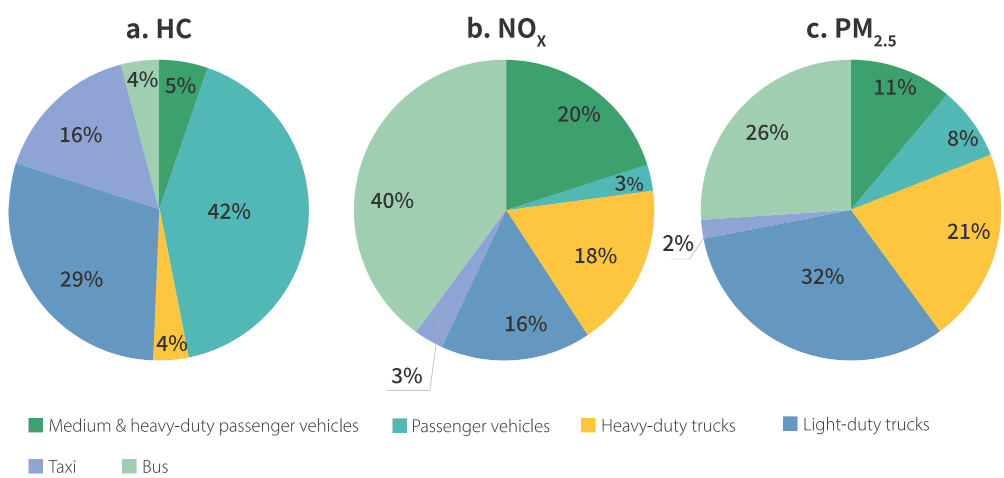
2 Prediction of future benefits from large-scale fleet electrification in Shenzhen in 2030

To meet the long-term goals of clean air and carbon neutrality, the process of continuously promoting NEVs is an important direction for Shenzhen and many other cities. This report provides a comprehensive assessment of the environmental, climatic, and health benefits of the large-scale electrification in Shenzhen by 2030.

The scenario comprehensively considers several important factors that affect NEV adoption, such as policy orientation and vehicle technology development. In 2030, the electrification rate of light-duty passenger vehicles was estimated to increase to 30% in Shenzhen and that of medium-duty and heavy-duty passenger vehicles were estimated to be 25–35%. For trucks, it is expected that the electrification rate of light-duty trucks will increase to 70%, owing to the rapid electrification of diesel-powered logistic vehicles. The electrification rate of medium-duty trucks will increase to 60%, and the proportion of electric heavy-duty trucks will increase to 15%.

Under this electrification scenario, the road transport sector will reduce 5,000 tonnes of HC (equivalent to a total HC emissions reduction of 37%), 6,000 tonnes of NO_X (43%), and 140 tonnes of $PM_{2.5}$ (42%). As shown in Fig 5.13, light-duty passenger cars, light-duty trucks, and taxis were the leading contributors to HC reductions (42%, 29%, and 16%, respectively). For NO_X, buses, medium- and heavy-duty passenger vehicles, medium- and heavy-duty trucks, and light-duty trucks were major contributors, contributing 40%, 20%, 18%, and 16% of the total NO_X reductions, respectively. The leading contributors to $PM_{2.5}$ reductions were light-duty trucks, buses, and medium- and heavy-duty trucks, contributing 32%, 26%, and 21%, respectively.

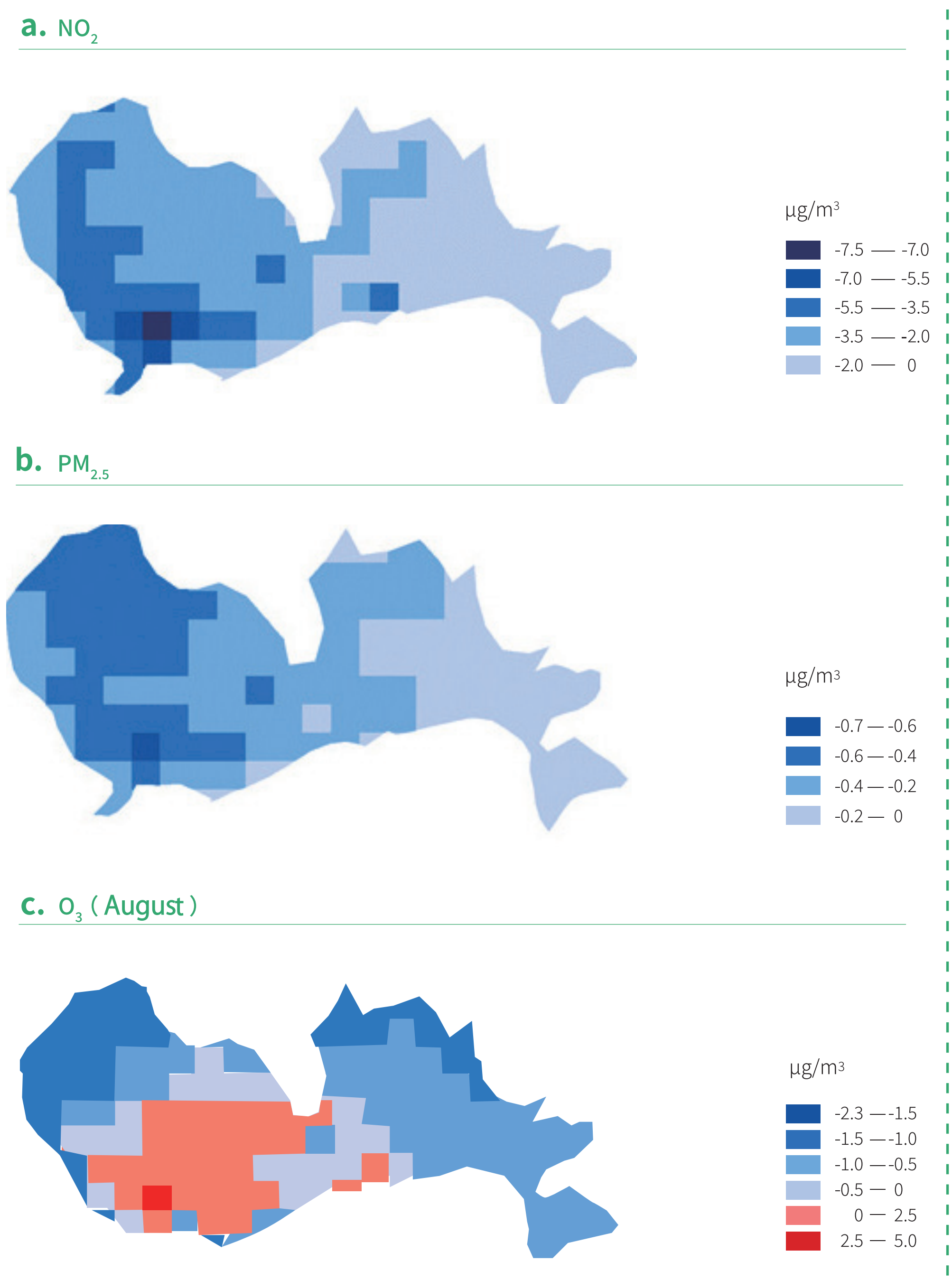
Fig 5.13. Emission reduction contribution by vehicle category for the future electrification scenario



Electrification has also led to a continuous and substantial reduction in GHG emissions. Shenzhen is expected to reduce its well-to-wheels GHG emissions by ~5 million tonnes by 2030. Passenger vehicles, trucks, and other public fleets (e.g., buses and taxis) contributed 48%, 31%, and 21% to GHG emissions reduction, respectively.

The CMAQ/2D-VBS model was used to simulate air quality benefits after large-scale electrification in Shenzhen (Fig 5.14). Notably, NO_2 can be significantly reduced in the electrification scenario, with an annual reduction of 4.1 $\mu g/m^3$ in traffic-dense areas. For areas covering nearly 176 km^2 with potential non-attainment risks, electrification is estimated to help 55% of these areas meet the annual NO_2 standard. It is estimated that in the future, the annual-average $PM_{2.5}$ concentration in traffic-dense areas will decrease by 0.4 $\mu g/m^3$. As for O_3 pollution, special attention has been paid to the peak seasons (summer) and high-concentration areas. The simulation results indicate that in areas with relatively higher O_3 pollution levels (e.g., northwestern Shenzhen), the summertime maximum daily 8-hour average (MDA8) O_3 concentration could decrease by 0.5-2.3 $\mu g/m^3$ due to electrification. In urban areas where the O_3 concentrations are relatively low, the simulated MDA8 will increase slightly after electrification because of the volatile organic compound (VOC)-limited regime during O_3 formation.

Fig. 5.14. Spatial distribution of the variations in the concentration of major pollutants in the future electrification scenario in Shenzhen in 2030



Improvements in air quality due to large-scale electrification can provide considerable health benefits. Under the electrification scenario, approximately 160 deaths could be avoided in Shenzhen in 2030, which would be equivalent to 1.7 billion CNY in monetization benefit. Due to high population density and remarkable air quality benefits, health benefits were pronounced in urban areas; the health benefits within urban areas account for about 90% of the total health benefits in the entire city of Shenzhen.

source: Pixabay

06 CHAPTER

Chengdu

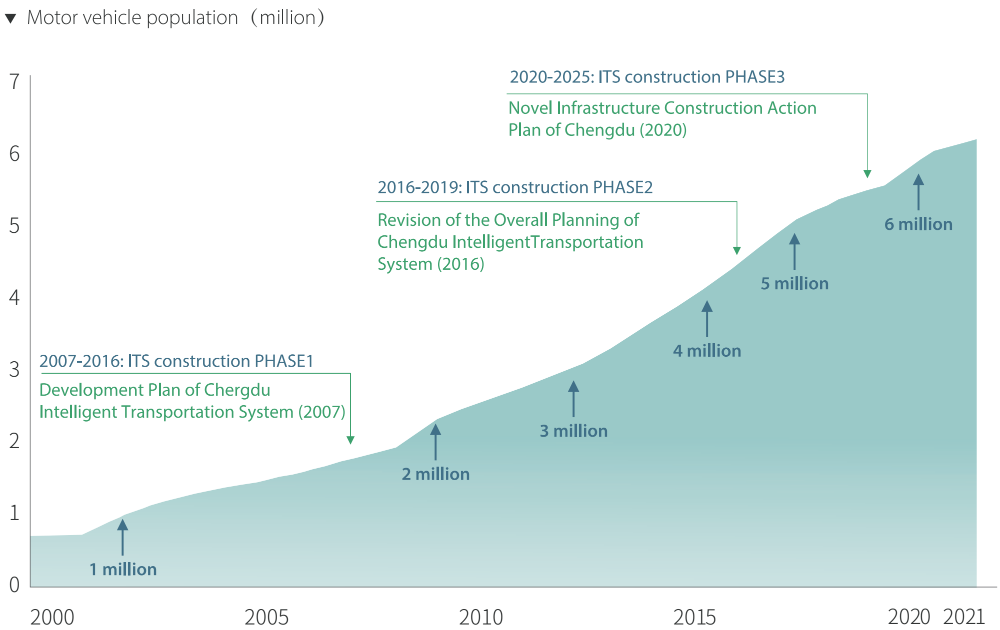
Big-data intelligent transportation system promotes precise emission control

Chengdu, the prominent business and financial center of Southwest China, serves as a crucial national high-tech industrial base, key logistics node, and comprehensive transportation hub. Over the past 20 years, with the continuous advancement of China's Western Development Drive policy, the economy of Southwest China has experienced rapid growth, leading to a substantial increase in the automotive market. The total number of registered motor vehicles in Chengdu has grown remarkably, increasing nearly tenfold since 2000 (Fig 6.1). By the end of 2021, the total vehicle population in Chengdu exceeded 6.2 million, making it the city in China with the second-highest total vehicle population, following Beijing. Currently, the automobile ownership in the city stands at 300 vehicles per 1000 people. While thriving motorization represents Chengdu's social and economic achievements, it has also resulted in dense traffic and environmental burdens.

In contrast to other megacities, like Beijing, Shanghai, and Shenzhen, Chengdu has not implemented license control measures to cap the growth of its total vehicle population. However, Chengdu has taken a proactive approach to address traffic and environmental issues through intelligent data-informed technologies and control policies. In recent years, the city has prioritized the development and utilization of intelligent transportation systems (ITS). Using high-density traffic detectors, Chengdu has established a monitoring network capable of gathering massive real-time data on traffic volume and speed. Building on this intelligent big data, a comprehensive decision-making system was developed to

promote smart monitoring and improve the management of vehicle emissions. The experience gained from implementing big-data ITS analytics for fine-grained transportation emission management can offer innovative solutions to other cities facing similar challenges due to rapid motorization.

Fig. 6.1. Motor vehicle population in Chengdu during 2000–2021



6.1

Development of intelligent transportation systems (ITS) in Chengdu

ITS encompass advanced applications of communication, control, and information technologies, with the goal of innovatively upgrading traffic management and user services. These systems aim to improve traffic efficiency, enhance road safety, and reduce energy consumption and traffic emissions. In recent years, significant progress has been made in the development of ITS, enabled by advanced technologies like mobile phone networks, global positioning systems (GPS), in-vehicle navigation, and vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications. These technologies have allowed for automatic real-time collection and remote monitoring of traffic information, resulting in an exponential

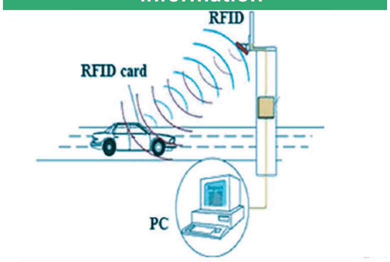
Fig. 6.2. Road traffic detectors in Chengdu

increase in data volume, spatial coverage, timeliness, dynamics, and precision - marking the emergence of the big data era in transportation.

One notable improvement in traffic monitoring systems is the transition from sparse and decentralized sensor distributions to more intensive layouts. Furthermore, data sources have expanded from single to dynamic and traditional monitoring technologies such as induction coils, have been replaced by electronic monitoring methods like video recordings, GPS-based floating vehicles, radio frequency identification (RFID), smartphone applications, and other novel techniques. Fig 6.3 showcases the various monitoring methods and the different types of traffic data that can be obtained, providing a rich and versatile database for fine-grained traffic emission supervision and decision-making.

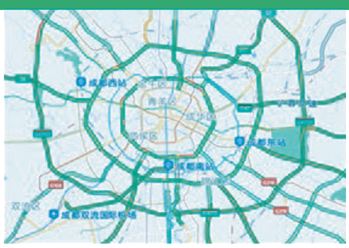
Fig. 6.3.Typical ITS and multi-source traffic data

RFID real-time traffic flow information



Detailed vehicle flow, location, speed, etc.

Congestion map



Operational status of roads, traffic speed, etc.

Traffic checkpoints

Detailed vehicle flow, location, speed, etc.

Floating cars monitoring system

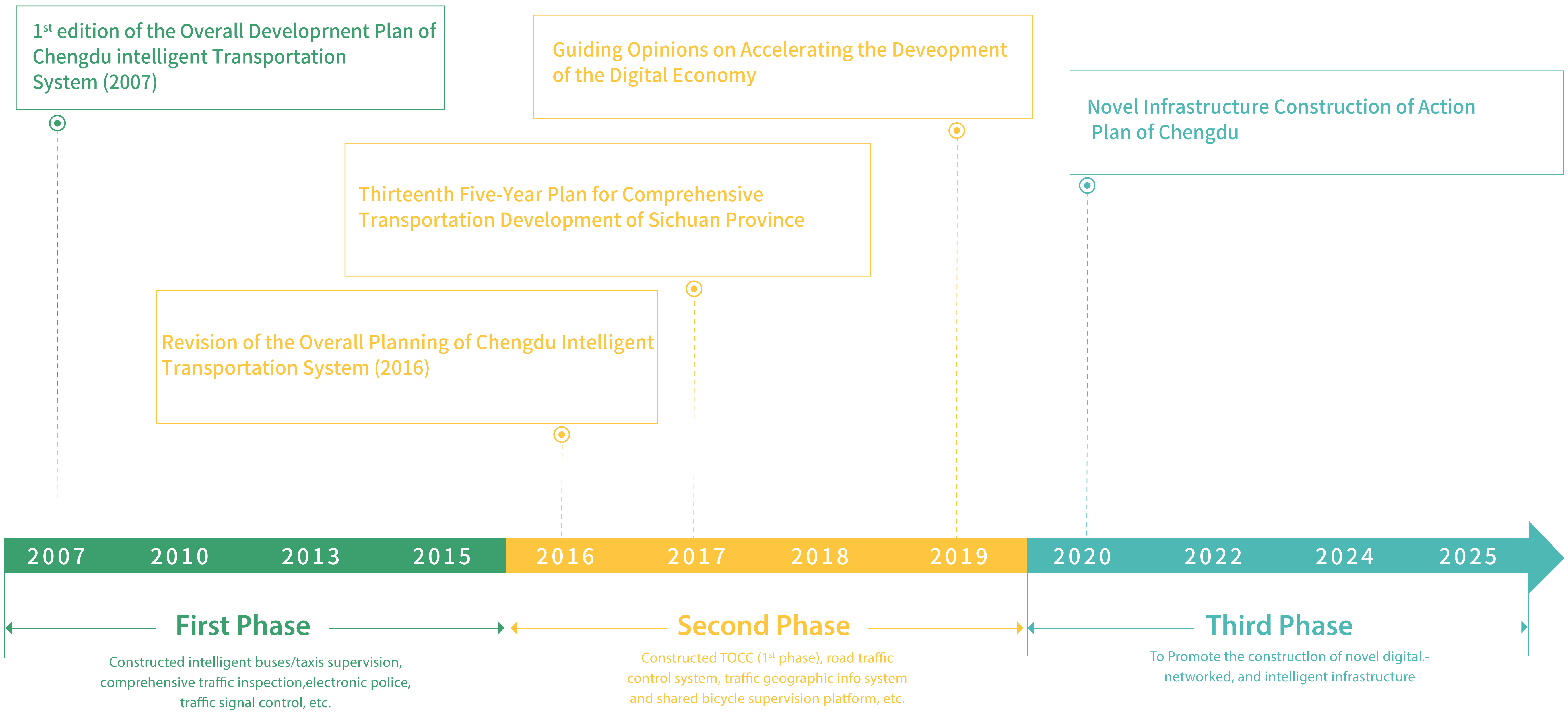
Location, speed, etc.

Chengdu initiated the construction of its ITS and its associated data platforms in 2007 (Fig 6.4). The first two phases of construction have been completed, and the third phase is underway. In 2007, Chengdu released the first edition of the "Development Plan of Chengdu Intelligent Transportation System" (2007) which laid the groundwork for the first phase of the project. This initial phase involved the development of intelligent supervision for buses and taxis, comprehensive traffic inspection, electronic police, traffic signal control, and other traffic management and control systems.

Building on the experience gained from the first phase, Chengdu revised its ITS planning in 2016 and released the "Amendment of the Development Planning of Chengdu Intelligent Transportation System" (2016), which provided guidelines for ITS development until 2021. The second phase focused on expanding and improving of Chengdu's ITS, which included the construction of a traffic operation coordination and command center (Phase I), road traffic control system, traffic geographic information system, and shared bicycle supervision platform.

With the rapid digital development and expansion of 5G applications, Chengdu has entered the third phase of ITS development. In this stage, the city aims to promote the construction of a novel digital network and intelligent infrastructure, with a focus on innovative application of 5G technology in intelligent transportation, intelligent logistics, and other relevant fields. These efforts are expected to drive the transformation and upgrade of traditional transportation infrastructure, expand the construction of NEV charging infrastructure, and foster innovative applications of artificial intelligence and big data in transportation.

Fig. 6.4. Development of big-data ITS in Chengdu



6.2

Development of vehicle emissions mapping and management system in Chengdu, based on traffic big data

During the vigorous development of ITS applications in Chengdu, a high-density network of traffic monitoring was constructed, laying a solid foundation for smart traffic emission management. Fig 6.5 illustrates that presently, over 4,000 traffic volume sensors are deployed in the central area of Chengdu, collecting real-time traffic flow data. These sensors enable the acquisition of fleet composition data, including vehicle segment, fuel type, and emission standard, through online matching with the registration database. Additionally, 34 highway monitoring sites distributed across the inter-city areas of Chengdu provide information on traffic flow and fleet composition for inter-city freeways. Open-source map applications, like AutoNavi maps, supply real-time link-level vehicle speed data.

Fig. 6.5. High-density traffic monitoring network in Chengdu

However, the current monitoring system still exhibits a significant gap in its coverage of the entire road network. To fulfill the data requirements for building high-resolution, network-level emission inventories, accurate and efficient simulations are necessary to fill the spatial gaps in traffic profiles. Traditional methods based on population or road densities for traffic activity allocation result in high uncertainty and are inadequate for constructing high-resolution inventories. In contrast, machine learning, with better adaptability to large datasets and higher computational efficiency, aligns well with the practical need for multisource traffic data fusion and real-time processing.

Tsinghua University has developed the Chengdu Vehicle Emissions Mapping and Management System, which features fast response times and powerful visualization capabilities. The system integrates a high-density traffic flow monitoring network, a full-network traffic-flow simulation method, and a localized emission factor model (Fig 6.6). Decision makers can intuitively observe high-resolution spatiotemporal distributions of vehicle emissions and the contributions of different vehicle segments through this system, enabling the development of targeted management policies for controlling vehicle emissions. The system's algorithms and interface user-friendliness have been continuously improved and optimized over years of demonstration and application. The latest version (V4.0, released in 2021) of the comprehensive decision-making system can support fast, accurate, and high-resolution vehicle emission simulations for the entire city. Moreover, it enables a continuous 72-hour real-time display of link-level traffic flow and vehicle emissions, along with benefit analyses for short- and long-term emission control scenarios. Overall, the platform enhances the timeliness, precision, and intelligence of traffic emissions supervision, providing significant technical support for decision-making regarding vehicle emissions control in Chengdu.

Fig 6.7 demonstrates how the new platform facilitates real-time query function for the entire road network or single-road vehicle flow and emissions. It dynamically presents traffic flow and real-time pollutant emissions for each major vehicle category for 72 consecutive hours. By clicking on a road, traffic flow and emissions for that particular road can be effectively observed, allowing for road-level refined emissions supervision.

Fig. 6.6. Upgrading the on-road motor vehicle emissions mapping and management system in Chengdu

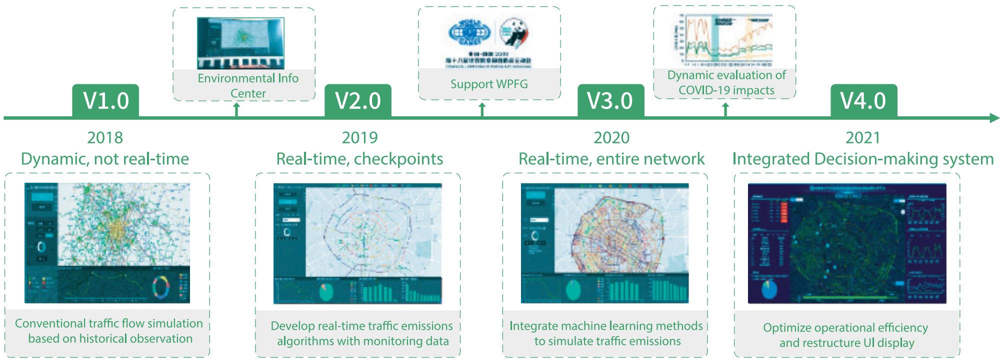


Fig. 6.7. Real-time query function of the whole road network/single road vehicle flow and emissions presented by the platform (V4.0, released in 2021)

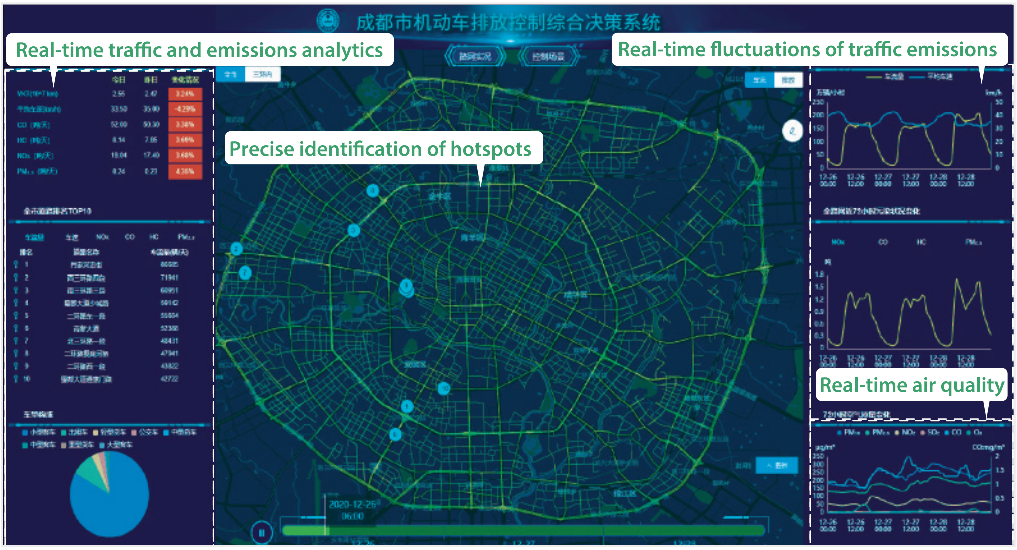
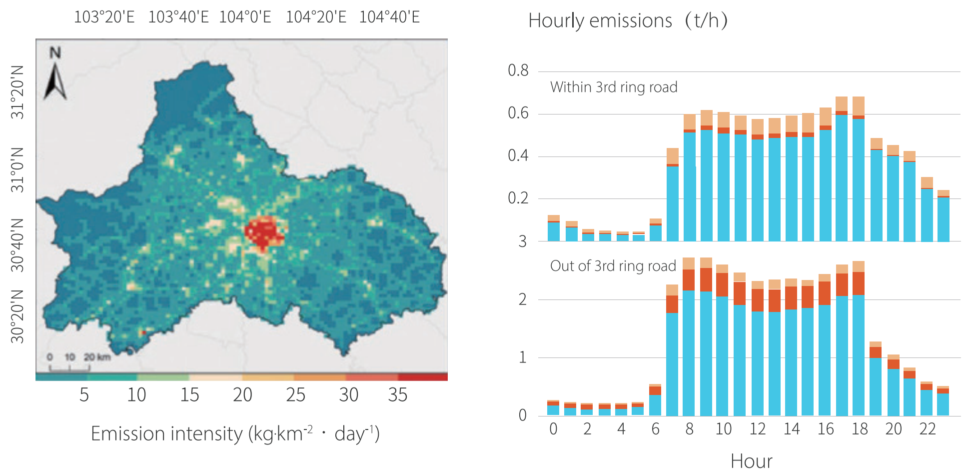


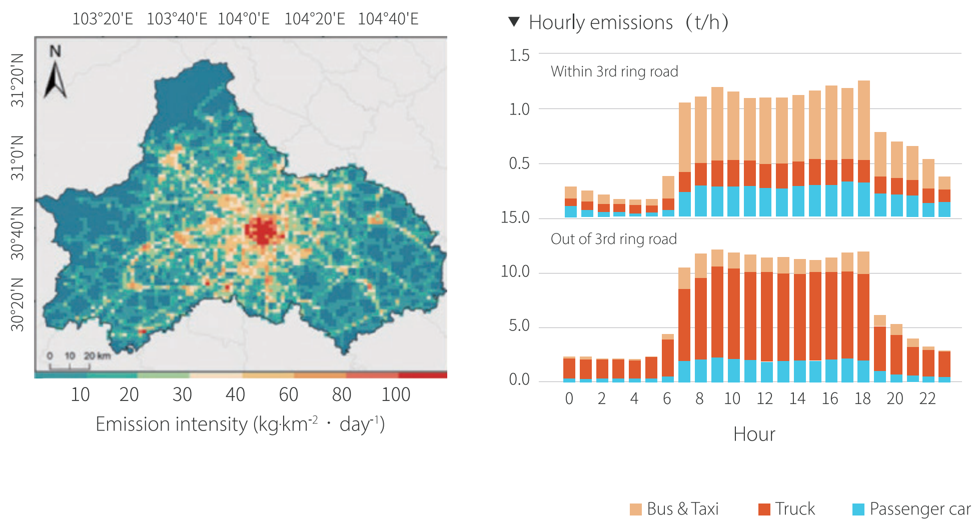
Fig 6.8 illustrates the spatiotemporal distribution of vehicle emissions for the entire road network in 2019, along with the emissions contribution by vehicle category. Notably, a significant urban-intense spatial feature of the emissions can be observed, with higher densities in the urban core, sub-centers, and connected arterial roads, gradually decreasing radially from the urban center. Within the Third Ring Road, HC emission intensity is significantly higher, with passenger cars accounting for 85% and 78% of the total HC emissions inside and outside the Third Ring Road, respectively. NO_X emission hotspots are present within the Third Ring Road and along freight corridors, where public transportation (buses and taxis) contribute 51% within the Third Ring Road and passenger cars contribute 28%. Trucks out of the Third Ring Road account for an overwhelming 70% of NO_X emissions. These findings emphasize the need for tailored control strategies based on pollutants and regions. For example, controlling HC emissions requires attention to the central city area and the passenger car fleet, with accelerated processes for eliminating or restricting high-mileage passenger cars. For NO_X, focus should be on areas with logistics centers and freight channels, strengthening emission supervision, encouraging the retirement of old heavy-duty trucks, and promoting the electrification of public vehicle fleets in urban areas.

Fig. 6.8. Spatiotemporal distribution of daily emissions from the entire road network in Chengdu and emission contribution by vehicle category

a. HC

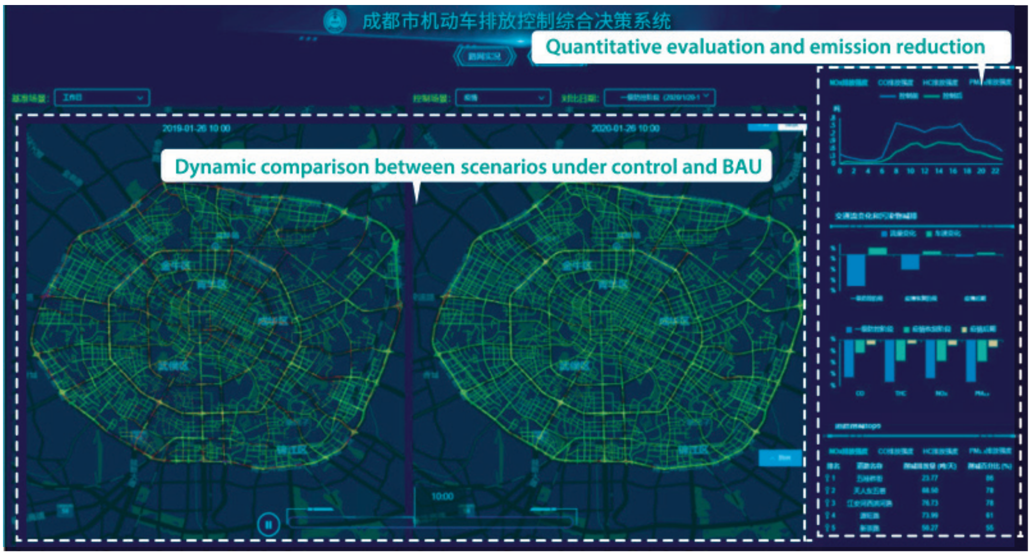


b. NO_X



An essential function of the Chengdu Vehicle Emissions Mapping and Management System is to quantitatively evaluate traffic changes and emission reduction benefits for different control policies, increasing its accuracy and supporting decision-making (Fig 6.9). The system can dynamically track traffic and emission changes during events like the COVID-19 pandemic and assess the benefits of traffic emissions control for major events, such as enhanced traffic control during the Chengdu World Police and Fire Games. Specific case studies supporting these policies will be elaborated on in the next section.

Fig. 6.9. Evaluation of policy benefits of the vehicle emissions mapping and management system implemented in Chengdu



6.3

Assessment of fine-grained vehicle emission controls

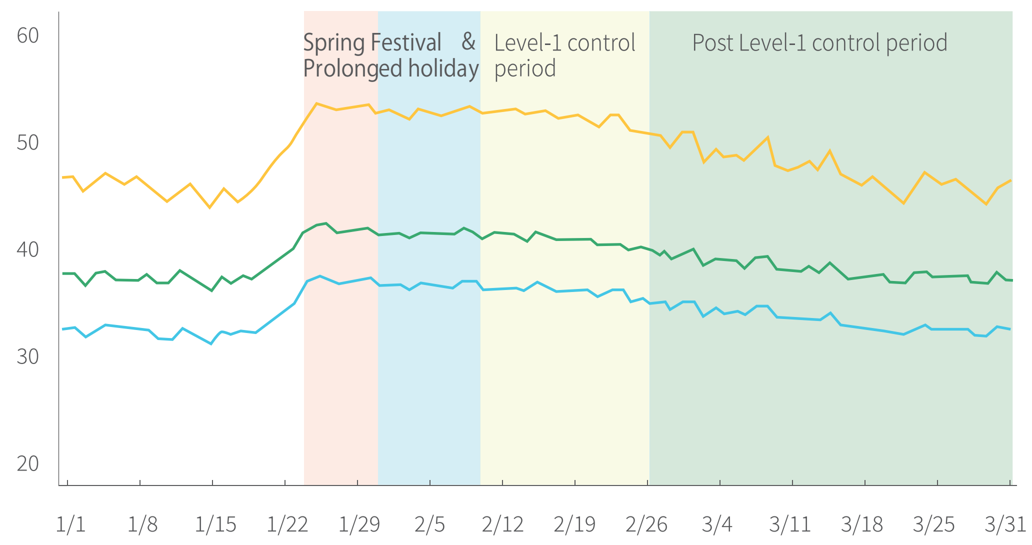
1 Case 1: Assessment of emission reduction benefits of traffic changes in Chengdu during the COVID-19 pandemic

The COVID-19 outbreak in early 2020 significantly impacted on residents' daily lives and the social economy. The pandemic led to a sharp reduction in traffic activities, creating a unique opportunity for conducting a large-scale natural experiment to evaluate the emission reduction resulting from changes in traffic during this period. Tsinghua University collaborated with the Chengdu Institute of Environmental Sciences to track and assess local traffic and emission changes using the Chengdu Vehicle Emissions Mapping and Management System. Fig 6.10 illustrates the real-time dynamic changes in traffic speed and flow for different road types (highways, arterial roads, and minor roads) in Chengdu during the COVID-19 lockdown (from January 2020 to March 2020). The first-level prevention and control measures in Chengdu were in place from January 24, 2020, to February 26, 2020 (shown in pink, blue, and yellow areas in the figure). During this period, the traffic flow in Chengdu decreased significantly (by 59%), while the average speed increased by 16%. As COVID-19 restrictions gradually eased, and residents were no longer under home quarantine, traffic activity in Chengdu gradually recovered and rebounded to pre-COVID-19 levels by mid to late March 2020. Notably, Chengdu was one of the largest cities in China to return to normal life within just two months of the outbreak.

Fig. 6.10. Changes in vehicle speed and traffic flow within 3rd ring road of Chengdu from January 2020 to March 2020

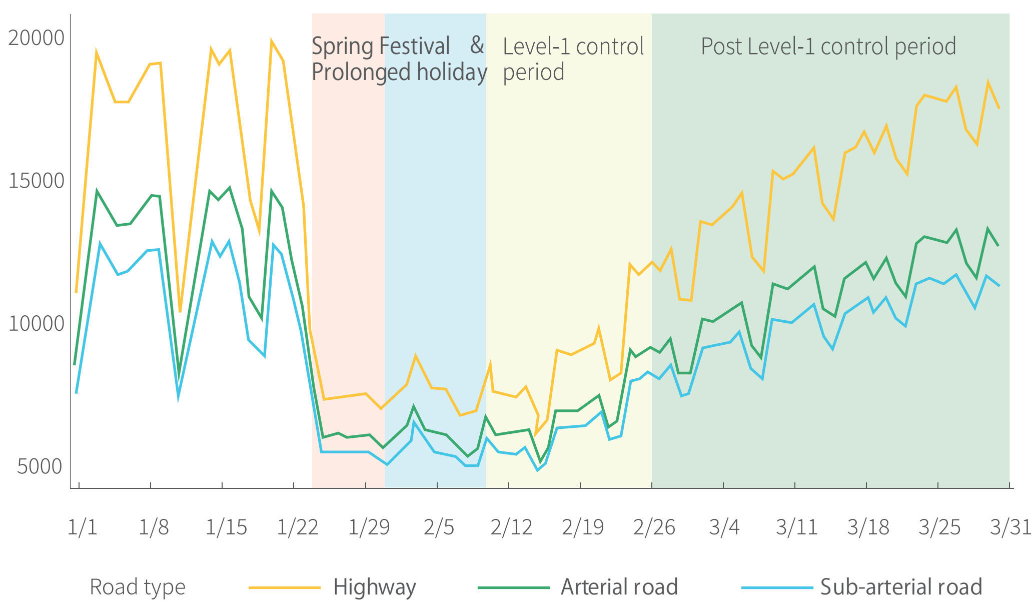
a. Daily average speed

▼ Daily average speed (km/h)



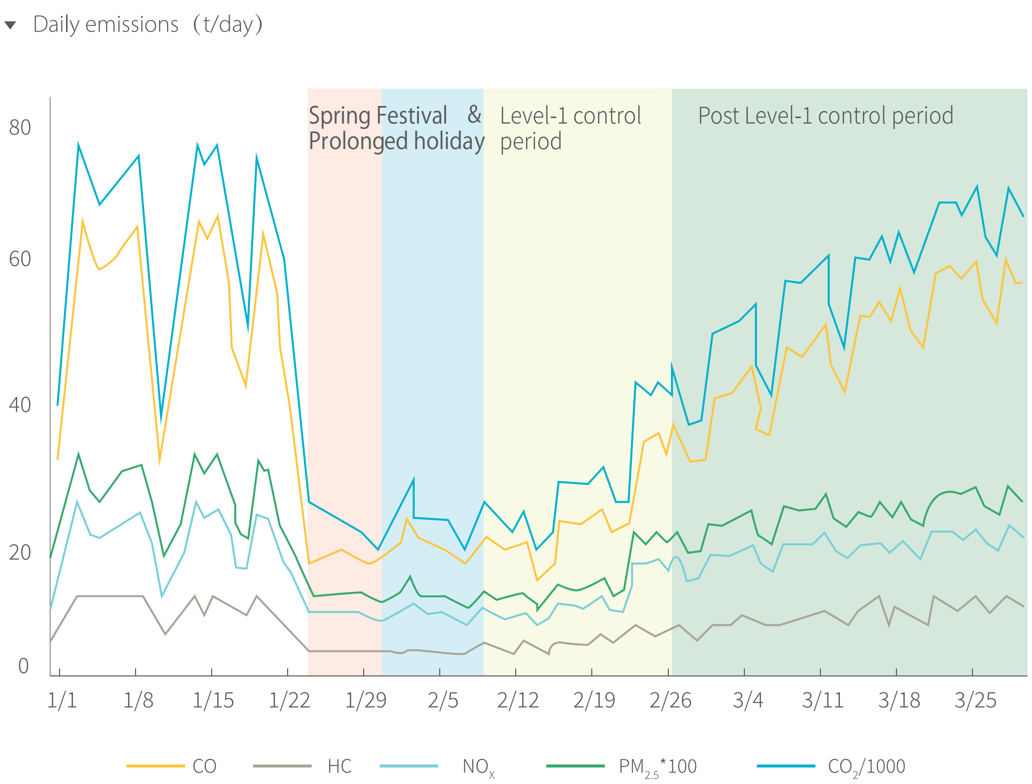
b. Daily total traffic flow

▼ Daily total traffic flow (veh/day)



The contraction of traffic activities during the control period led to a substantial reduction in vehicle emissions of all air pollutants. However, as the first-level control measures were lifted, emissions began to rebound, and by the end of March, they returned to pre-pandemic levels. Different stages of the epidemic reflect variations in vehicle emissions under different levels of traffic reduction. For instance, during the first-level control stage, the vehicle emission reductions of CO, HC, NO_X, $PM_{2.5}$, and CO_2 within the Third Ring Road were as high as 64%, 64%, 54%, 55%, and 62%, respectively. As restrictions were lifted and traffic activities gradually recovered, the reduction benefits of CO, HC, NO_X, $PM_{2.5}$, and CO_2 decreased to 23%, 23%, 12%, 14%, and 22%, respectively, by early March. Eventually, by the end of March, vehicle emissions returned to pre-epidemic levels. In general, the emission reductions of NO_X and $PM_{2.5}$ were relatively lower compared to those of CO, HC, and CO_2, possibly due to buses, taxis and trucks being the main contributors to NO_X and $PM_{2.5}$ emissions, and their traffic reduction was lower than that of passenger cars.

Fig. 6.11. Changes in air pollutants and CO_2 emissions for on-road transport in Chengdu from January 2020 to March 2020



BOX 6-1

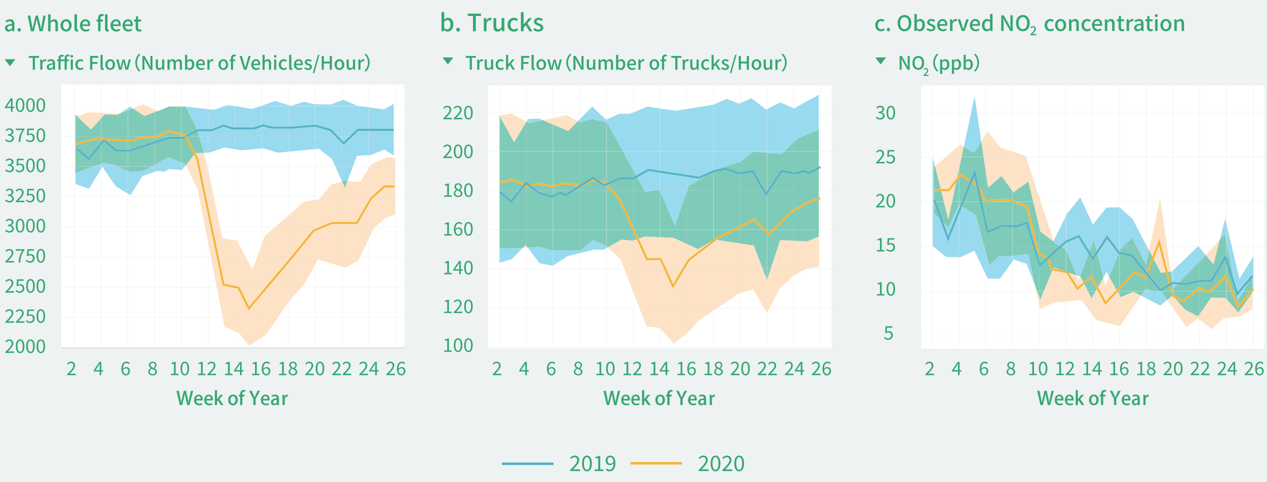
Evaluation of vehicle emission reduction in Los Angeles during COVID-19

Tsinghua University applied an integrated method to assess the impact of the COVID-19 lockdown on vehicle emissions in Los Angeles (LA), California. Collaborating with research scientists from the California Institute of Technology, they developed a dynamic traffic emission modeling system for the greater LA area. Using machine-learning model, they established a dynamic air-quality simulation method that provided an instantaneous response to pollutant concentration, meteorological data and traffic factors. This approach enabled an accurate and efficient assessment of traffic emission reductions and their effects on air quality in LA during the COVID-19 lockdown. The results were published in the Proceedings of the National Academy of Sciences in 2021.

During the most stringent period of the COVID-19 lockdown, the traffic volume of passenger cars and trucks in LA decreased by 37% and 28%, respectively. As a result, traffic emissions of CO, HC, NO_X, and $PM_{2.5}$ decreased by 38%, 37%, 35%, and 35 %, respectively. This reduction led to a 2.9 ppb (-30 %) and 1.1 $\mu g/m^3$ (-18%) decrease in the NO_2 and $PM_{2.5}$ concentrations, respectively, and a 2.1 ppb (5.7%) increase in the MDA8 O_3 concentration. The changes in truck traffic contributed 61%, 70%, and 82% to the changes in NO_2 , $PM_{2.5}$, and MDA8 O_3 concentrations, respectively. Compared to Chengdu, the proportions of traffic emission reduction and air-quality changes in LA were relatively lower. Therefore, the impact of the lockdown measures on traffic emissions in LA was smaller but lasted longer.

The system, based on traffic big data, can track real-time traffic changes and evaluate the benefits of emission reduction from various control measures, providing scientific support for mobile emissions supervision and air quality management in other cities around the world.

BOX Fig 6-1. Traffic flow and NO_2 concentration during (2020) and before (2019) the COVID-19 pandemic in Los Angeles



BOX 6-2

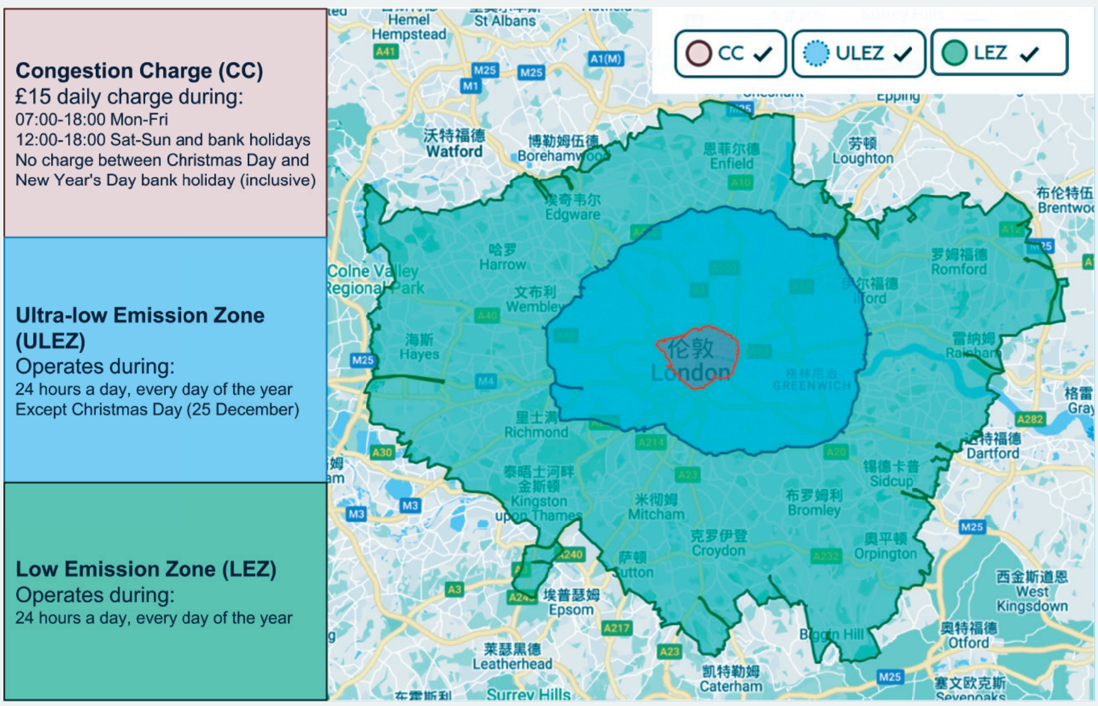
Low emission zone (LEZ) in London

London was the first city in the world to implement a LEZ policy. The city has had a congestion charge in place since 2003, and the LEZ policy has been active since 2008. In 2019, an ultra-low emission zone (ULEZ) was introduced, with even stricter entry requirements. Notably, in October 2021, the ULEZ was expanded to cover a larger area (BOX Fig. 6-2). At present, vehicles that fail to meet the stringent emission standards are charged £12.50 per vehicle per day for driving within the zone.

London's LEZ scheme relies on an automatic license plate recognition system to monitor vehicles. When a vehicle's license plate information is captured at a checkpoint, it is cross-referenced with the registered vehicle database to verify if the vehicle has the necessary permission or if it meets the payment requirements. Vehicle owners can complete the payment on a dedicated website or set up a fixed payment method for automatic deductions. The charge amount is doubled if the payment is not made on time.

Since the implementation of the congestion charge and LEZ, the vehicle population in London has remained stable, with an average annual growth rate of less than 0.3% from 2010 to 2020. In 2019, the share of local residents' green travel increased to 63% of the total on-road transportation modes. Additionally, in 2020, the average roadside NO_2 concentration in downtown and inner London areas decreased by 50% and 40%, respectively, compared to 2010. Thus, the LEZ has significantly contributed to reducing vehicle emissions and improving urban air quality in London.

BOX Fig 6-2. Scope of LEZ in London



Source: https://tfl.gov.uk/

2 Case 2: Coordinated benefit assessment of traffic flow and pollutant emissions for LEZ policy

The LEZ concept refers to a designated area where access to certain high-emitting vehicles is restricted or discouraged to improve regional air quality and traffic conditions. Within the LEZ, only vehicles meeting specific emission standards are permitted to enter during designated time periods, while vehicles failing to comply with the regulations are either banned or subject to penalties. The LEZ policy has emerged as a crucial measure for many countries and regions to tackle air pollution issues arising from traffic. Representative cities implementing LEZ policies include London, Paris, and Stockholm.

International experience indicates that the LEZ policy is effective in reducing vehicle use, promoting fleet turnover, alleviating traffic congestion, and reducing air pollution, all while maintaining low economic costs. To achieve these goals, an ITS is required to ensure effective vehicle identification and timely payment.

Chengdu already has a solid foundation for ITS infrastructure but is currently facing challenges due to rapid growth in transportation demand and high vehicle emissions. Implementing the LEZ can lead to an optimized travel mode, improved operational efficiency, and reduced traffic emissions. Consequently, the LEZ is expected to make a significant contribution to Chengdu by helping to alleviate traffic congestion, and improve air quality.

Fig. 6.12. Regular low-emission zone (LEZ) and ultra-low emission zone (ULEZ) in Chengdu

The feasibility and environmental impact of implementing the LEZ policy in Chengdu were studied by the Chengdu Institute of Environmental Sciences, in collaboration with Tsinghua University and Shenzhen Urban Transport Planning and Design Institute. The team used the Chengdu Vehicle Emissions Mapping and Management System tool to assess the traffic and environmental impacts of the LEZ policy. Drawing from the experiences of LEZs in other cities worldwide, the team established a low emission zone that covers the downtown area (area within Beltway) and two ultra-low emission zones in Chengdu (Fig 6.12).

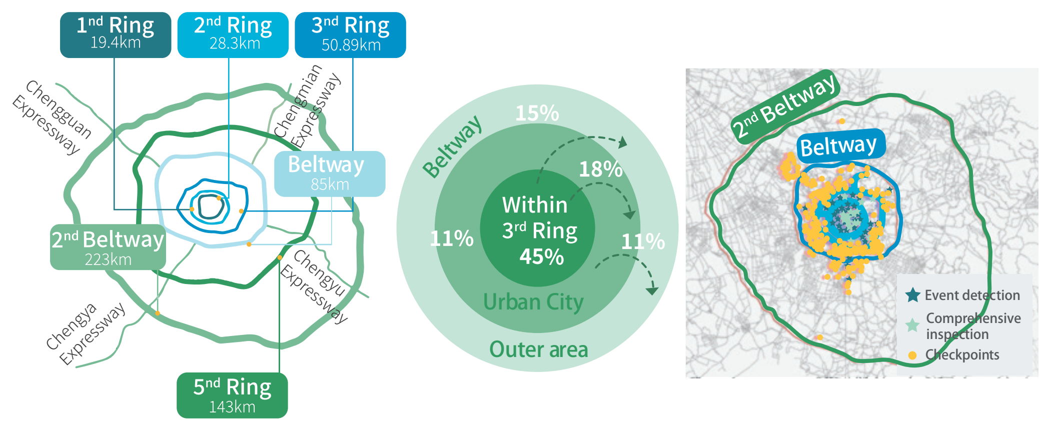
Chengdu's urban highway network follows a "ring + radial" structure, with high population density and traffic within the Beltway area (Fig 6.13a). Although the inner area of the Beltway accounts for only 3.5% of Chengdu's total area, it accommodates 37% of the city's population and motorized travel. Restricting trips across the Beltway area would affect approximately a quarter of all trips across the Beltway area (Fig 6.13b), a contribution comparable to the impact of LEZs in cities like London. In terms of infrastructure, Chengdu currently has over 2,800 traffic monitoring sites and regulation enforcement facilities within the Beltway area (Fig 6.13c). These monitoring facilities serve multiple functions, including event detection, vehicle speed monitoring, and traffic flow monitoring, indicating that the inner city is technically ready to implement a LEZ. If a restricted area is established within the Beltway in Chengdu, the monitoring execution rate may even surpass that of cities like London and Paris. Therefore, considering indicators such as travel intensity, traffic conditions, and infrastructure service, the Beltway can be designated as the boundary of a regular LEZ (Fig 6.12). Regarding restricted vehicles, approximately 20-30% of the total fleet conforms to China 3/III emission standards. Following international experience which involves affecting 10-20% of vehicles, the restricted vehicles are designated as diesel trucks meeting China III and below and gasoline passenger cars meeting China 2 and below emission standards.

Fig. 6.13. Spatial information about the trips and traffic monitoring sites of Chengdu

a. Chengdu's Ring-shape Road Network

b. Share of Traffic OD

c. Traffic Monitoring Sites



Further, an ULEZ was considered within the regular LEZ. The ULEZ adopts stricter entry permissions, encouraging the use of NEVs and green transport modes to ensure good air quality. The scope of the ULEZ was designed based mainly on traffic operations, population and employment structures, and social needs.

Based on traffic characteristics, heavy congestion was likely to occur on the entire First Ring Road and within the high-tech zone (such as the Financial City area) located on the south side of the Third Ring Road during the morning and evening peak hours. Additionally, hospitals and schools within the First

Ring Road and the Financial City area of the southern high-tech cone are densely distributed, making patients and students particularly sensitive to air quality. Thus, these areas require good air quality. Consequently, the First Ring Road and the Financial City area were designated as the pilot areas of Chengdu's ULEZ (Fig 6.12). Considering Chengdu's fleet structure, the restricted vehicles included all diesel trucks; gasoline passenger cars and gasoline light-duty trucks that followed the China III emission standards or the standards implemented before them.

Different congestion charges and entry permissions were set up based on the characteristics of the two areas. The First Ring Road is a closed-ring road with good road conditions; therefore, the toll access system is more appropriate for this road. Within the Financial City area, many business trips occur during peak hours, with a high proportion of motorized trips. Therefore, congestion charging during peak hours can be considered.

The specific traffic control rules for the LEZ (within the Beltway) and the two ULEZs (within the First Ring Road and the Financial City areas) are summarized in Table 6.1. Notably, the traffic restrictions of the LEZ were lenient, whereas those of the ULEZ were stricter. To comprehensively evaluate the policy impacts, two scenarios were designed. The first scenario consisted of a regular low-emission zone (LEZ S1), which only considered setting the area within Beltway as the LEZ. In the second scenario, LEZ S2, two ULEZs were added to LEZ S1.

Table 6.1. Detailed control measures for the LEZ and ULEZ in Chengdu

Area	Control measures
Within Beltway (LEZ)	1. Trucks: Diesel trucks of China III emission standards and below were banned 24 h a day 2. Cars: Cars of China 2 emission standards and below were banned 24 h a day 3. Cars: China 3 cars were banned during peak hours (7:00–9:00 & 17:30–19:00) on weekdays 4. Non-local registered vehicles followed the same restrictions as local vehicles, monitored through manual inspection; warnings were issued for the first three violations, with punishments for subsequent violations 5. See notes for exemptions
Within First Ring Road (ULEZ)	1. Trucks: All diesel trucks were prohibited from entering 2. Cars: Cars of China 3 emission standards and below were prohibited from entering 3. The baseline parking fee was increased to 20–25 yuan 4. Cars that did not meet ULEZ standards had to purchase a pass or complete payment by day 5. Non-local registered vehicles followed the same restrictions as local vehicles, monitored through manual inspection, warnings were issued for the first three violations, with punishments for subsequent violations 6. See notes for exemptions
Within Financial City area (ULEZ)	1. Trucks: All diesel trucks were prohibited from entering 2. Cars: Cars of China 3 emission standards and below were prohibited from entering 3. Cars: China 3 cars were charged during peak hours (7:00–9:00 & 17:30–19:30) 4. The baseline parking fee was increased to 20–25 yuan 5. Non-local registered vehicles followed the same restrictions as local vehicles, monitored through manual inspection; warnings were issued for the first three violations, with punishments for subsequent violations 6. See notes for exemptions

Notes: Vehicles entitled to an exemption include: 1) vehicles with new energy vehicle (NEV) license plates; 2) specialist vehicles for the disabled, driven by disabled people with C5 driving licenses; 3) taxi, buses, military vehicles, police vehicles, fire rescue vehicles, ambulances, engineering rescue vehicles, and sanitation vehicles, such as sprinklers, sewage suction vehicles, and garbage trucks; 4) vehicles with embassy and consulate license plates and foreign vehicles that have temporary permission to enter; and 5) other vehicles specified by laws and regulations that are not restricted by driving routes and directions.

Fig. 6.14.Spatial distribution of motor vehicle emissions reduction rates within Beltway in different scenarios

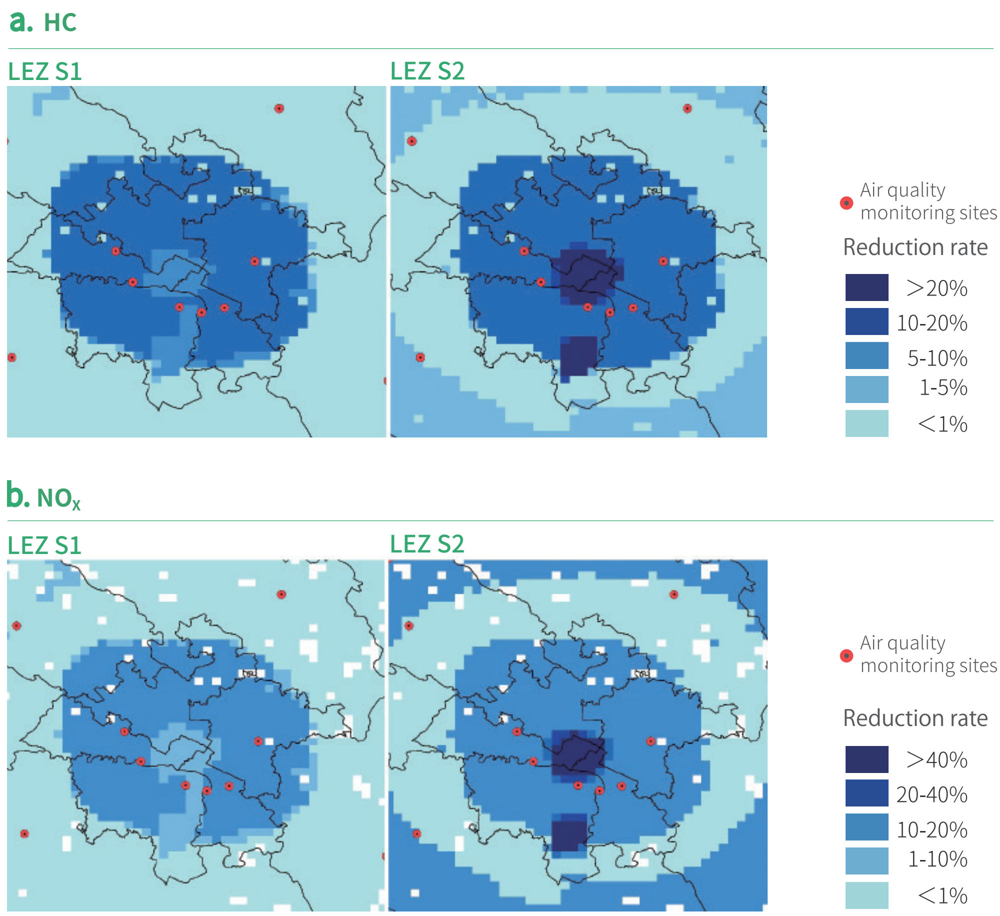
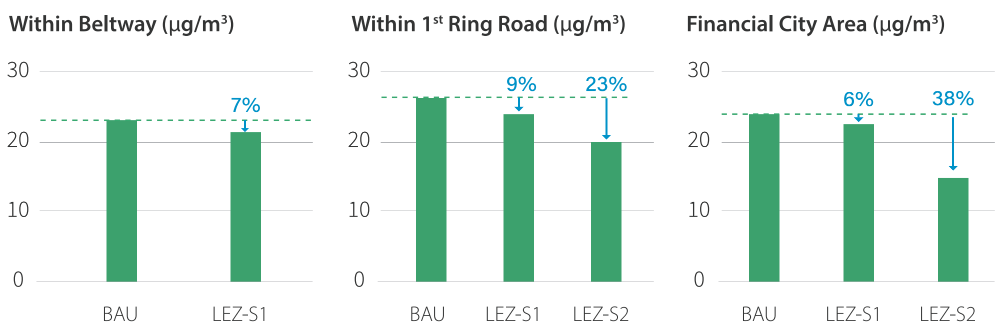


Fig. 6.15. Average NO_2 concentration reduction benefits in different scenarios (simulated concentrations directly from vehicles)



The simulation results indicated that traffic trips and total mileage within the restricted areas would decrease after the implementation of the LEZ policy. Specifically, traffic activities in the LEZ decreased by 5-7%, while those in the ULEZs decreased by 7-14%. The Chengdu Vehicle Emissions Mapping and Management System allowed for a high-resolution spatial distribution visualization of the emission reduction rates within the Beltway for different scenarios (Fig 6-14). In the LEZ-S1 scenario, the HC and NO_X emissions were estimated to reduce by 9-12% and 8-12%, respectively. However, the reduction benefits were not as satisfactory within the First Ring Road and the Financial City area, due to less strict restriction measures. Therefore, in the LEZ-S2 scenario (stricter), the two ULEZs could achieve more significant benefits, with a 24-29% reduction of HC and as high as a 39-70% reduction of NO_X.

Using the RapidAir model, the improvement in roadside NO_2 concentrations was evaluated for the two scenarios (Fig 6.15). In the LEZ-S1 scenario, the roadside NO_2 concentrations could be reduced by 6-9% compared to the Business-As-Usual (BAU) scenario. However, in the LEZ-S2 scenario, the reduction benefits of NO_2 concentrations within the First Ring Road and Financial City areas could increase to 23% and 38%, respectively.

Thus, the implementation of the LEZ policy can significantly reduce traffic intensity and vehicle emissions, thereby improving the city's air quality. Additionally, the LEZ policy can be integrated with the promotion of NEVs and transportation structure adjustments. This approach would enrich the LEZ as a "green and low-carbon demonstration zone," leading to substantial mitigation of air pollutants and CO_2. Such a concept could serve as a crucial pathway for developing green and low-carbon transportation systems in large cities.

However, it's essential to acknowledge that LEZ implementation can be complicated and may require legal support and the establishment of ancillary infrastructure in advance. Therefore, careful consideration of all stakeholders and their concerns should be taken into account before implementation. Moreover, dynamic tracking and thorough evaluation are necessary both before and during implementation to ensure its effectiveness. An accurate vehicle identification and emission accounting system is a significant prerequisite for ensuring the policy's authority. To successfully implement LEZs, efforts should be made to minimize the side effects of the policy on residents' lives. This can be achieved by continuously developing public transportation options and promoting of non-motorized transportation such as biking and walking, to improve travel convenience for residents.

07 CHAPTER

Summary and outlook

7.1

Summary

The automotive market in China has witnessed remarkable growth over the past three decades, due to significant socioeconomic development and urbanization. While rapid motorization has brought various benefits, such as industry upgrading, social progress, and travel convenience, it has also posed substantial challenges related to air pollution, public health, energy security, and climate change. Recognizing the issue of air pollution caused by vehicle emissions in the mid-1990s, China took cues from successful experiences in developed countries and embarked on a journey of learning and improvement.

Over the last 20 years, China has implemented a series of actions and plans to tackle the challenges including continuous upgrades to emission standards, improvements in fuel quality, in-use vehicle emission control, promotion of NEVs, and optimization of traffic management. Consequently, an integrated control system encompassing "vehicle-fuel-traffic" was developed and progressively refined. These efforts have been successful in effectively mitigating vehicle emissions, despite a significant increase the number of vehicles leading to the successful decoupling of motorization from the growth of on-road emissions.

Megacities in China, particularly Beijing, Shanghai, Shenzhen and Chengdu, have been pioneers in adopting of advanced vehicle emission control measures. Their experiences have not only contributed to the ongoing optimization of vehicle emission control systems in China but also offered valuable references for other cities to explore green and low-carbon development paths for their transportation systems. Below are some key experiences from vehicle emission management in these cities and at the national level over the last two decades.

01 Simultaneous implementation of vehicle emission and fuel quality standards

The tightening of emission standards has been the cornerstone of the vehicle emission control system's success over the last 20 years. In January 1999, Beijing took the lead by implementing China 1 emissions standards (equivalent to Euro 1) for light-duty gasoline vehicles (LDGVs). Since then, Beijing has consistently adopted more stringent vehicle emission standards than other cities, becoming a trailblazer in vehicle emission control in China. In 2020, Beijing implemented the China 6/VI emission standards, aligning with the most stringent regulations worldwide. These continuous improvements in emission standards not only propelled the upgrading of the automotive industry but also ensured a cleaner vehicle fleet in the city.

Moreover, Beijing's success underscores the importance of simultaneous implementation of emission and fuel quality standards to maximize the benefits of vehicle emission standards. In the 1990s, Beijing began improving its fuel quality by gradually phasing out leaded gasoline (1997) and high-sulfur-content fuels (2012). When the nationwide implementation of emission standards faced delays due to lagging fuel quality standards, Beijing proactively adopted fuel standards in line with China 2/II to 5/V emission standards, ensuring synchronous implementation with emission standards. Beijing's proactive approach to fuel quality standards serves as a model for synergistically improving vehicle emissions and fuel quality in China. As a result, Beijing's experience has influenced the nationwide simultaneous implementation of emission and fuel quality standards in the China 5/V emission standards and the unification of on-road and non-road diesel fuel standards in the China 6/VI stage.

Over the last 20 years, the synchronized tightening of emission and fuel quality standards has made the most significant contributions to vehicle emission mitigation in Beijing, accounting for 74%, 73%, 66%, and 55% of the reduction in on-road CO, HC, NO_X, and $PM_{2.5}$, respectively.

02 Integration of multiple advanced technologies for emission monitoring of in-use vehicles

In real-world scenarios, vehicle emissions often exceed permissible limits, making effective supervision of in-use fleets crucial for on-road emission control. Over the course of two decades, China has developed a comprehensive inspection system that integrates multiple technical means for in-use vehicles, along with a regular supervision mechanism.

To strengthen the I/M program, Beijing has continuously adopted advanced technologies to detect exhaust components of in-use vehicles. Notably, in 1999, the city revised the two-speed idle test method and standard limits for new China 1 vehicles. Subsequently, the more stringent acceleration simulation mode method was fully implemented in 2003, with updates to emission standards. For in-use diesel vehicles, Beijing introduced a lug-down test in 2003, further tightening smoke emission limits. The implementation of these advanced methods and stricter emission limits has significantly improved the identification of high emitters.

In recent years, Beijing has enhanced its real-world emission monitoring systems by promoting the application of advanced supervision technologies and accelerating the construction of supervision platforms. A range of advanced technologies, including roadside remote sensing, portable emission measurement systems (PEMS), and remote on-board diagnostics (OBD) tests, have been employed in Beijing. In particular, OBD has been utilized to monitor the compliance of in-use heavy duty diesel vehicles due to concerns about real-world NO_X emissions. Since 2018, Beijing has piloted the OBD retrofit for China IV and China V in in-use heavy-duty trucks, requiring the installation of OBD devices. Regulations regarding OBD installation and data transmission at the China VI level were also implemented in advance. As a result, an online monitoring platform with 100,000 in-use heavy-duty vehicles has been established.

The use of powerful and efficient remote OBD technology, has led to a 50-70% reduction in NO_X emission levels for Beijing's heavy-duty diesel vehicles (HDDVs) compared to China V trucks without OBD monitoring. This significant reduction in NO_X emissions has contributed to mitigating $PM_{2.5}$ and NO_2 pollution. Furthermore, the NO_X emissions from diesel trucks in Beijing decreased by 43% compared to 2017, surpassing California's reduction from 2010 to 2020 (~37%). Consequently, NO_2 concentrations in Beijing decreased by 37% over the three years, meeting air quality standards for the first time in 2019.

03 Effectiveness of “Prioritizing Public Transport” strategy and optimization of freight transportation structures

Reshaping public transport systems and encouraging sustainable green travel modes are fundamental measures for cities to develop green and low-carbon transportation systems during urbanization process. Cities, like Shanghai and Beijing, place significant emphasis on optimizing public transportation systems and non-motorized travel modes to cope with the increasing transportation demand while transitioning to efficient, green, and low-carbon transportation.

Shanghai, as the pioneer in China, established the “Prioritizing Public Transport” strategy as a key component of urban development. Along with urban and transport planning, Shanghai has implemented a series of policies to develop subways, optimize bus routes, and promote public and non-motorized transport. Coupled with the restrictive policy, these efforts have significantly improved the urban transportation structure and effectively alleviated traffic-related environmental issues. Over the years, the proportion of public transport in all motorized travel increased from 43% in 2000 to 47% in 2020. Presently, Shanghai’s subway lines cover over 700 km, a tenfold increase compared to 2000. The city boasts approximately 500 km of bus-only lanes, and bus stops are fully covered within a 300 m radius in the central area. Furthermore, vehicle ownership density in Shanghai is controlled at approximately 180 vehicles per 1,000 people, the lowest among domestic megacities with similar GDP per capita. Notably, in the past two decades, Shanghai has successfully followed a green and low-carbon transportation development path, combining the public transportation priority strategy with comprehensive control of traditional vehicle emissions.

China's freight structure heavily relies on road transport. The “Three-Year Action Plan for Winning the Blue-Sky Defense” and the “Three-Year Action Plan for Promoting Transportation Structure Adjustment” have played a crucial role in adjusting the transportation structure to control diesel truck pollution. To promote the “road to rail’ and “road to water” shift for bulk cargo transportation, government departments have implemented several economic measures and policies supporting infrastructure construction. These efforts have led to a notable change in the predominance of road transportation. The share of railway cargo transportation has grown, with an annual average growth rate of nearly 7% from 2017 to 2020, while the share of road cargo transportation decreased from 78% in 2017 to 74% in 2020. Additionally, the transportation structure of bulk goods in coastal ports in the Bohai Rim region and Yangtze River Delta has been significantly optimized. However, compared to the proportion of railway freight, which was higher than 30% in 1980, the adjustment of the transportation structure is still in its initial stage.

04 All-round development and promotion of NEVs

The promotion of NEVs holds significant benefits in reducing pollutants and carbon emissions. It is crucial for China to develop clean and efficient modern energy systems to achieve a green and low-carbon industrial transformation, aligning with its long-term goals of clean air and carbon neutrality.

Shenzhen is one of the first cities to actively promote NEVs and has been recognized as the "Capital of Electric Vehicles in the World" for six consecutive years. Currently, Shenzhen has successfully introduced nearly 400,000 NEVs, accounting for 11% of its total vehicle stock. Notably, the city boasts the highest electrification rate among all megacities in China. Shenzhen also stands out as the world's first city to achieve complete electrification of bus and taxi fleets, while its number of electric trucks has consistently ranked first globally for the past five years.

The rapid development of electric vehicles in Shenzhen can be attributed to the comprehensive construction of supporting systems and a well-planned NEV industry layout. Over the past decade, the city has issued more than 30 standards and administrative rules directly related to NEVs. Additionally, a comprehensive support system has been established, including development planning, standard specifications, financial subsidies, and infrastructure construction. Shenzhen has introduced diverse subsidy and incentive measures for NEVs, covering different aspects of the life cycle including purchase, usage, infrastructure, and battery recycling. Fiscal incentives have played a crucial role in promoting NEV adoption in the city. Furthermore, Shenzhen has strategically focused on the layout of the new energy industry, hosting over 2,000 NEV-related enterprises, making it one of the cities with the highest density of NEV companies globally.

The rapid development of NEVs in Shenzhen has become a crucial component in achieving the city's local clean-air action plan, known as "Shenzhen Blue". Since 2014, NO_2 concentrations in Shenzhen have significantly improved, with 35% of this improvement attributed to fleet electrification. The city anticipates that further large-scale promotion of NEVs will continue to enhance its air quality, including coordinated control of $PM_{2.5}$ and O_3 pollution. This shift towards NEVs is expected to minimize health risks for residents while substantially contributing to the whole life-cycle reduction of GHG emissions from on-road traffic.

05 Diversification of transportation energy and application of biofuels

Biofuels play an important role in China's pursuit of diversified, clean, and low-carbon transportation energy. Over the past two decades, China has actively conducted pilot applications of biofuels for vehicles. In recent years, there has been a constant promotion of ethanol gasoline to optimize the energy structure, improve the ecological environment, reduce CO_2 emissions, and address overstocked aged grains. In 2017, 15 ministries, including the National Development and Reform Commission, issued documents to promote ethanol gasoline, and the overall structure of the ethanol industry for biofuel production was identified. Presently, E10 ethanol gasoline is sold in 15 provinces in China at varying scales, with a proposed supply of nearly 3 million tonnes of bioethanol.

To address the food safety issue arising from the reuse of waste cooking oil ("gutter oil"), Shanghai has established a closed-loop management system for the entire industry chain of waste cooking oil treatment. This system covers various aspects of the process, such as collection, transportation, storage, disposal, and application of gutter oil. Shanghai has successfully applied B5 and B10 biodiesel on a large scale in buses and heavy-duty vehicles. Presently, the amount of waste cooking oil collected in Shanghai exceedes 200 tonnes per day, which can be converted into more than 50,000 tonnes of B100 biodiesel annually, replacing nearly 1% of transportation diesel consumption. These measures not only benefit emission reduction and energy conservation but also provide valuable insights for other cities aiming to diversify their transportation energy sources.

Notably, the scale of biofuel promotion in China still lags behind that of the USA and Brazil. In 2020, bioethanol production was 41.6 MT and 24.3 MT in the USA and Brazil, respectively, while biodiesel production in the EU was 13.6 MT. In light of China's commitment to reaching its CO_2 emission peak by 2030 and achieving carbon neutrality by 2060, greater efforts are needed to promote the research and development of biofuels in the country.

06 Big-data intelligent transportation system promotes precise vehicle emission control

The development of intelligent transportation technology and the utilization of traffic big data are key trends for transitioning to precise and intelligent traffic emission control strategies. Instead of implementing license control measures to cap the growth of the total vehicle population, as seen in other megacities in China, Chengdu is committed to solving its traffic and environmental issues through intelligent data-informed technologies. In recent years, Chengdu has made significant efforts to develop and utilize ITS. The city established a monitoring network with around 4,000 high-density traffic detectors operating within the urban area, providing real-time traffic volume and fleet-mix data. Integrated with a machine learning based traffic flow simulation method, Chengdu has developed a dynamic vehicle emission mapping and management system. The latest version (V4.0, released in 2021) of this comprehensive decision-making system can support fast, precise, enabling high-resolution vehicle emissions simulations for the entire city, and a continuous 72-hour real-time display of link-level traffic flow and vehicle emissions. The platform also allows for the simulation of benefit analysis for short- and long-term emission control scenarios, this enhancing the timeliness, precision, and intelligence of traffic emission supervision systems. This platform has proven successful in dynamically tracking traffic and emission changes during the COVID-19 pandemic, assessing the LEZ policy, and enhancing traffic control during major events (e.g., Chengdu World Police and Fire Games), providing significant technical support for precise decision-making in vehicle emission control.

The assessments of the feasibility and expected effects of the LEZ policy indicate that its implementation in Chengdu can significantly reduce traffic intensity and vehicle emissions, leading to an improvement in the city's urban air quality. Furthermore, the LEZ policy can be integrated into the promotion of NEVs and transportation structure adjustments, transforming the LEZ into a "green and low-carbon demonstration zone," thus achieving deep mitigation of air pollution and CO_2 concentration. This concept could become an important pathway for building green and low-carbon transportation systems in large cities. However, the implementation of the LEZ policy is a systematic project that requires advanced legal support and ancillary infrastructure. Therefore, careful consideration of all stakeholders and their concerns is crucial before implementation. Moreover, dynamic tracking and careful evaluation are necessary before and during the policy's implementation. The experience of applying big-data ITS analytics to achieve fine-grained vehicle emission management provides innovative solutions for other cities facing similar challenges resulting from rapid motorization.

7.2

Outlook

China's achievements in vehicle emission control are inspiring, but there is still a long way to go. Most importantly, China's vehicle market is projected to continue growing steadily, with the total stock being expected to reach 400-500 million by 2030. As a result, building a sustainable, green, and low-carbon transportation system becomes the core challenge in the future development of China's transportation sector.

01 Deep emission abatement is critical for continuous air quality improvement and synergic response to climate change

The amendment to air quality standards by the World Health Organization (WHO) in 2021 has further restricted the limits for crucial pollutants, including $PM_{2.5}$, O_3, and NO_2. In the four targeted cities of Beijing, Shanghai, Shenzhen, and Chengdu, the $PM_{2.5}$ concentration is between 20-35 $\mu g/m^3$, significantly higher than the 10 $\mu g/m^3$ level found in international megacities, like New York, London, and Tokyo, and far beyond the new WHO guidance of 5 $\mu g/m^3$. Notably, the issue of O_3 pollution is also severe and demands more scientific and precise vehicle emissions control measures. In response to a similar O_3 concentration problem, California has already announced clear policies for profound NO_X emission reduction from mobile sources. China has also identified synergic control and emission reduction for $PM_{2.5}$ and O_3 as critical tasks for air quality management during the 14^{th} Five-Year Plan. Improving air quality and reducing the frequency of heavy-polluting days are significant goals for China to achieve its "Beautiful China" objective by 2035. Thus, continuous emission reduction is a critical task for air quality improvement in China's megacities in the short- and mid-term.

Additionally, China has announced ambitious double carbon targets to achieve a carbon emission peak by 2030 and carbon neutrality by 2060. In the past decade, China's transportation sector has contributed the most to the increase in carbon emissions, with the highest annual emission growth rate being 6%. On-road vehicles, as the dominant part in the transportation sector, contribute 80% of the total transportation emissions. Achieving the 2060 carbon neutrality target will require improvements in vehicle energy efficiency, optimization of transportation structure, and a transition to clean energy on a long-term scale. This will lead to significant synergic benefits in remarkable pollutant emission abatement and air quality improvement.

02 Enhance the leading role of standards and technologies and tighten the restriction for emission control of internal combustion engine vehicles (ICEVs)

As of now, California continues facing a high O_3-concentration problem, despite over half a century of management and control efforts. In response, California has announced plans to strengthen O_3 control, making the reduction of NO_X, a significant precursor to managing O_3 concentrations, crucial for future regulatory work. The CARB has approved the next generation of ultra-low limits for NO_X emissions from heavy-duty vehicles, with this stringent limit value being over 90% lower than the China VI standards. Similarly, the European Union (EU) vehicle emission regulations' consultancy group has proposed tightening the HDV NO_X emission limit by 90% in the Euro VII standard. Furthermore, future emissions standards will focus more on real-world vehicle emission performance, being technology- and fuel-neutral, and regulating additional pollutants as an extension to the tightening of the emission limits for NO_X, THC, and NMHC, with the serious consideration for synergic control of GHG emissions. For example, future standards are expected to include high-activity atmospheric precursors, such as NH_3 and HCHO, and set limits for non-CO_2 GHGs, including CH_4 and N_2O.

The guidance of these more stringent emission standards will bring both challenges and opportunities for original equipment manufacturers of automobiles and engines, as more advanced engine and after-treatment technologies will be required. Two technology roadmaps combining selective catalytic reduction (SCR) + exhaust thermal management and passive NO_X absorber (PNA) + SCR have been proposed for compliance with ultra-low NO_X emission standards. Additionally, with the direction of the double carbon targets, improvements in energy efficiency and CO_2 emission reduction technologies are essential, alongside NEV development promotion and transportation structure optimization. The key technical focus for reducing CO_2 emissions from conventional ICE vehicles is expected to include hybrid powertrain and lightweight technology for light-duty vehicles, engine efficiency and stop cylinder technology for heavy-duty vehicles, exhaust energy management and powertrain electrification technology, and low-carbon biofuel technology.

03 Clean and low-carbon energy transition for transportation sector can promote the green development of automotive industry

Clean and low-carbon energy transition in the transportation sector is a fundamental measure to achieve multi-pollutant control and synergic CO_2 reduction. China has announced future targets to achieve a carbon emission peak before 2030 and carbon neutrality by 2060. Promoting NEVs will play an essential role in decarbonizing the transport sector and accelerating the mitigation of air pollutant emissions in the future.

In the light-duty vehicle sector, electric vehicles have already demonstrated a greater dominance in life-cycle CO_2 emission reductions compared to gasoline vehicles. With further improvements in the clean grid, electric light-duty vehicles will become increasingly competitive for carbon reduction. As the NEV subsidy gradually decreases, it is crucial to fully utilize the operational cost-effectiveness advantages of light-duty electric vehicles to contribute to China's carbon peaking target.

For commercial vehicles, promoting NEVs is a core task for achieving carbon neutrality in the mid- and long-term, presenting both great potential and challenges. Comprehensive consideration should be given to various NEV technologies and their application in different commercial vehicle (CV) types and operational modes. Early comprehensive studies on the environmental and cost benefits for different operational segments are necessary to establish a clear and appropriate commercial vehicle development plan based on the advantages of different NEV technologies. Currently, NEVs in China's CV markets are concentrated on city buses and light- and mid-duty trucks, with uncertainties surrounding the future development of heavy-duty trucks. It is crucial to regulate proper action plans and timescales for electric vehicle or hydrogen fuel-cell vehicle technologies and infrastructure development, based on economic costs and emission reduction potential of the technology. China's implementation of several pilot hydrogen projects in key regions offers an opportunity to scientifically evaluate the life-cycle CO_2 and air pollutant emissions from hydrogen fuel-cell vehicles and conduct parallel studies for hydrogen infrastructure development.

The production and usage of vehicles and fuels involve various industries and sectors, and the life-cycle emission reduction of vehicles and fuels can significantly impact the green development of upstream industries, such as battery, iron, steel, and aluminum manufacturing. Data integration for the energy, industry, and supply chains can be highly effective for long-term technology development and the promotion of NEVs and low-carbon biofuels. Implementing a full life-cycle emission evaluation platform for city-level or regional-level NEVs and clean energy can support this effort. The deep integration of energy and transportation systems can further promote the development of an intelligent NEV infrastructure system and an intelligent energy system, such as a battery swapping network or a smart charging network, which can significantly improve the convenience and emission reduction capabilities of NEVs.

04 Strengthening infrastructure development and improving service performance to facilitate green travel systems and optimize freight structure

Positive developments in public transportation have effectively mitigated the congestion problem in large and mid-sized Chinese cities with high population density. However, traffic congestion and pollution issues have not been fully resolved, making a green and intelligent public transportation system essential for sustainable development, despite the challenges. The principles of Public Transport

First, Non-motorized First, and Green First should persist, while a transition to low-energy-consumption, low-emission, and high-efficiency public travel is requested. Public transport efficiency and infrastructure should be strengthened, walking and biking experiences improved, and green public travel promoted.

The IoT and big data can significantly contribute to an intelligent public transport system, by integrating date from people, vehicles, routes, stations, and cloud data. This integration can enhance the public transport service and efficiency through functions such as optimized bus route plans, precise bus stop docking, and signal control priority. A public-friendly non-motorized transport system would also improve public engagement through cycling or walking, achieved by enhancing their experience, establishing special lanes and ensuring non-motorized transport security. Incentives, such as carbon-inclusive mechanisms, can also instill motivation to participate in green public travel and lead the transition to a more environmentally friendly and low-carbon future.

While road freight's dominance has weakened due to freight transportation structure adjustments in key regions and industries, more challenges need to be solved. Firstly, for gate-to-gate freight transport, on-road transport holds great cost advantages over rail transport, especially for short- and mid-distances. Secondly, rail capacity may not be sufficiently competitive in several regions with poor development and high costs. Therefore, efforts should focus on building rail freight infrastructure and improving rail services to promote freight structure adjustment. The main target should be to increase the capability of multimodal transport, forming a better freight system where rail and maritime pathways dominate for mid- and long-distance transport of bulk cargos, belt corridors, and new energy transport for short distances. Accordingly, road-to-rail and road-to-maritime plans have been developed for different industrial parks. For instance, coal transport in Jing-Jin-Ji and surrounding areas can implement road-to-rail measures, while the Yangtze River Delta and Guangdong-Hong Kong-Macao Greater Bay areas are suitable for rail-to-water or river-to-ocean multimodal transport plans.

05 Exploring intelligent and innovative solutions to manage vehicle emissions in the era of the IoT and big data

The prospect of achieving profound vehicle emission reduction relies heavily on precise vehicle emission evaluation, real-time road network inspection, and intelligent transport management. The technologies combining intelligent sensing and big-data, such as remote OBD integrated with link-based emission inventories , will play critical roles in future smart management systems. Additionally, these technologies can be further applied for pollution and emission inspection allowing for synergistic pollutant and GHG emission control management in key regions and cities. This may be used to inform critical policy decisions on NEV promotion, green public travel, and freight structure adjustments, with abundant vehicle energy efficiency, driving cycles, and footprints.

In the coming years, intelligence and interconnectedness will be the primary development trends for vehicle technologies. Under the Digital China Strategy, innovative and internet-connected vehicles and advanced infrastructure will be critical producers and beneficiaries of on-road transport big data. An increasing number of cities will build innovative, green, low-carbon, high-efficiency, and intelligent transportation modes by leveraging powerful advanced technologies, such as 5G, AI, big data, and cloud computation. This shift will lead to comprehensive supervision and optimized transportation systems that integrate vehicles, roads, and clouds data. The existing platform under the "sensing-decision" methodology will undergo an upgrade with a focus on becoming "digital, internet-connected, and intelligent." This will enable the realization of smart route plans and elegant cruising can be achieved in addition to precise management, and control, ultimately improving transport efficiency and contributing to air quality and double carbon targets.

Achieving green, low-carbon, and sustainable development in the transportation sector is a significant milestone in China's pursuit of the goal "Beautiful China." This requires a clear focus on creating a high-quality ecological environment and implementing comprehensive and synergistic control measures for pollutants and GHGs. Cities like Beijing, Shanghai, Shenzhen, and Chengdu, as pioneers in vehicle emission control, have made remarkable achievements in this regard. Their experiences can serve as valuable examples for other Chinese cities and the global community in advancing towards greener and more sustainable transportation practices.


source: Pixabay

A Retrospective and Prospective Study on 20 Years' Mobile Source Emissions Control in Megacities of China

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