



China Air 2025

Best Practices in Air Pollution
Prevention and Control

About Clean Air Asia

Clean Air Asia (CAA) is an international nongovernmental organization (NGO) leading the regional mission for better air quality and healthier, more livable cities throughout Asia. CAA was established in 2001 and is a United Nations-recognized partnership. CAA is headquartered in Manila, Philippines, with offices in Beijing, China, and New Delhi, India, as well as six country networks (Indonesia, Malaysia, Nepal, the Philippines, Sri Lanka, and Vietnam) and 261 partnerships in Asia and internationally.

CAA has been working in China since 2002 to improve air quality management as well as promote green transport and energy transition. The CAA China office was officially registered as a foreign NGO in China in March 2018 and has been conducting capacity building, research, and public education in air pollution control nationwide, guided by the Ministry of Public Security and our professional supervisory organization, the Ministry of Ecology and Environment (MEE).

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Foreword

Over the past decade, China has made sustained efforts in air pollution prevention and control, resulting in remarkable improvements in air quality. In 2024, the annual average PM_{2.5} concentration across 339 prefecture-level cities and above fell by 59% compared with 2013, while the number of heavy pollution days declined by more than 90%.

Since 2013, China has successively introduced the *Action Plan on the Prevention and Control of Air Pollution*, the *Three-Year Action Plan for Winning the Blue Sky Defense Battle*, and the *Action Plan for the Sustained Improvement of Air Quality*, gradually establishing a governance system with clearly defined targets, transparent responsibilities, and robust measures. By advancing industrial green transformation, fostering clean and efficient energy use, decarbonizing and greening transportation, and improving legal and regulatory frameworks, China has achieved continuous improvement in air quality. As control efforts deepen, refined management, technological support, and regional collaboration have emerged as key priorities.

Under national-level strategies, cities and regions play a critical role in air pollution control. As key fronts for policy implementation, cities can tailor policy design, management mechanisms, and governance models based on their industrial structures, pollution profiles, and development priorities, while regional collaboration helps address cross-provincial pollution and drives collective progress. Through diverse city practices and coordinated regional governance, not only has air quality improved locally and in neighboring areas; practical experiences have also been gained that are both replicable and scalable.

Identifying and distilling best practices and proven approaches will be essential to supporting China's air pollution control under the 15th Five-Year Plan period, as well as informing air quality management in regions across Asia and beyond that continue to face severe pollution challenges. In this context, CAA has developed this report, featuring five representative case studies that illustrate China's efforts in regional joint prevention and control, institutional innovation, emission reduction in key sectors, intelligent regulation, and scenario-based exploration. This report seeks to provide actionable insights for more regions and cities, support sustained air quality improvements, and help advance the transition toward a greener, healthier, and more sustainable future.

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Executive Summary

Over the past decade, China has achieved notable progress in air pollution control, with substantial reductions in major pollutant emissions and historic improvements in air quality. However, as control efforts deepen, the characteristics of pollution and the needs of governance are evolving, marking a shift into a new phase of intensified and upgraded air quality management. On the one hand, the simultaneous advancement of industrial upgrading, energy transition, and green transportation places greater demands on local governance capacity, technological support, and refined management. On the other hand, cross-provincial pollution transport has further underscored the need for enhanced regional collaboration.

At this new stage, the practices of cities and regions have become a critical lens for understanding China's progress and experience in air pollution control. In recent years, many cities and regions—drawing on their respective industrial structures, development contexts, and pollution profiles—have explored diverse pathways for air quality improvement. These include enhancing policy and regulatory frameworks; driving emission reduction in key sectors, such as industry and transportation; piloting innovative low-carbon or low-emission scenarios; and strengthening inter-regional cooperation. Such differentiated practices demonstrate both the innovation and adaptability of local actions in tackling complex air pollution challenges, while also providing a valuable reservoir of actionable experience that can be scaled up across China and inform efforts in other regions across Asia and beyond.

Systematically summarizing and scaling these practices will be essential to building a more advanced air pollution control framework and supporting future actions.

Against this backdrop, CAA has developed this report, which features five representative case studies: regional joint prevention and control in the Beijing–Tianjin–Hebei and surrounding areas; Beijing's regulation-monitoring-inspection (RMI) linkage model; the industrial VOC control of Shanghai; the intelligent supervision of heavy-duty diesel vehicle emissions in Shanghai; and the near-zero carbon construction site pilot in Chengdu. These cases focus on five key areas—regional collaboration, cross-sectoral coordination, deep emission reduction in key sectors, digital governance, and scenario-based explorations—showcasing innovations in policy implementation, management reform, technological application, and industrial transition.

Key Findings

Joint Prevention and Control in the Beijing–Tianjin–Hebei and Surrounding Areas: Advancing Regional Air Quality Through Efficient Collaboration

Constrained by high reliance on coal-based energy, heavy industrial activity, and truck-dominated freight transport, combined with complex geographic and meteorological

conditions, the Beijing–Tianjin–Hebei and surrounding areas (BTH Region) have long faced severe air pollution challenges and significant cross-provincial pollutant transport, which undermine the effectiveness of city-level measures. Since the efforts during the 2008 Beijing Olympic Games, the joint prevention and control mechanism in the BTH Region has gradually evolved into a nationally recognized model of regional air governance. Its main experiences can be summarized as follows:

- **Establishing a multi-level, cross-sectoral, and inter-regional governance system.** A national-regional-local hierarchy characterized by central coordination, regional alignment, and provincial and municipal implementation was established, ensuring that regional collaboration is institutionalized and systematic. Cross-sectoral cooperation has coordinated structural adjustments in energy, industry, and transport with emission reduction actions, providing solid institutional and strategic support for regional joint air pollution prevention and control. By aligning planning, standards, monitoring, and control measures, policy coherence and coordinated action have been effectively achieved.
- **Refining regional coordination mechanisms and strengthening emergency response.** Local governments across the region have established heavy pollution emergency response plans with tiered early warning systems and emergency response procedures. Enhanced 7–15-day air quality forecasting enables cities to issue timely early warning. Emergency emission reduction lists—covering industrial, mobile, and dust sources—have been continually refined and integrated with performance-based classification and refined management, enabling differentiated yet synchronized controls across the region. A

joint team has been built to evaluate emergency response effectiveness in heavy pollution episodes, creating a closed loop of problem identification, joint assessment, and local rectification and thereby advancing more targeted, science-based air pollution control.

- **Leveraging technology and finance to enhance regional governance capacity.** Technologically, efforts have been made to strengthen monitoring, early warning, and emergency response capabilities; develop intelligent regulation to support decision-making for emergency emission reduction; prompt research and development to reduce control costs; and enable source-level emission reduction in key sectors. Financially, both central and local governments have invested through a mix of subsidies, fees, rewards, pricing policies, and financial instruments to support emission control in major sectors, including coal use, motor vehicles, and industry, thereby facilitating the sustained and coordinated implementation of measures.

Through joint prevention and control, air quality in the BTH Region has improved significantly, with marked reductions in PM_{2.5} concentration, a sharp decline in heavy pollution days, and a noticeable increase in good or excellent air quality days. However, new pressures and challenges have emerged in such areas as governance systems, technological capacity, and coordination mechanisms. The next phase of action will require further enhancing forecasting capabilities, refining emergency emission reduction lists, developing comprehensive pollution control technologies, strengthening legal enforcement and regulation, and improving regional collaboration mechanisms—enabling sustained regional air quality improvements.

Beijing's Regulation-Monitoring-Inspection Linkage Model: Technology-Enabled Precision Governance for an Ultra-Large City

Focusing on targeted, science-based, and law-based pollution control, the Beijing Municipal Bureau of Ecology and Environment has pioneered an innovative RMI linkage mechanism—integrating overall planning/dispatching (regulation), perception-based initiation (monitoring), and targeted enforcement (inspection)—to build a data-driven, intelligently coordinated governance model. The main experiences can be summarized as follows:

- **Establishing an efficient and closed-loop governance system through cross-departmental and cross-level coordination.**

Within the RMI linkage mechanism, each department plays a distinct yet interconnected role: the environmental regulation department acts as the “engine,” coordinating and defining priorities; the environmental monitoring serves as the “sentinel,” identifying and analyzing problem clues; and the environmental enforcement department acts as the “iron fist,” tracing pollution sources and carrying out targeted enforcement actions. Together, they form a closed-loop response system. Beijing has also institutionalized an RMI joint meeting mechanism, RMI assistance mechanism, and RMI source-tracing mechanism, ensuring clearly defined roles, streamlined processes, and collaborative execution. Through the continuous dispatch of problem clues and rectification progress, the RMI linkage mechanism has strengthened accountability and mobilized efforts across districts, subdistricts (townships), and relevant departments, creating a cohesive citywide governance system.

- **Strengthening technological support to enable digital and intelligent regulation.** Leveraging artificial intelligence, the Internet of Things, vehicle-mounted monitoring, and satellite remote sensing, Beijing has built an integrated monitoring network characterized by “satellite observation, ground patrol, data networking, and electricity verification,” enabling the round-the-clock monitoring of various pollution sources. Intelligent algorithms enhance the precision of clue analysis across five dimensions: source, issue, location, timing, and response. A closed-loop dispatch system featuring “two-hour feedback and four-hour resolution” has been established—primarily for pollution response scenarios—supporting precise, intelligent dispatch and the closed-loop regulation of violations. With technological support, the RMI linkage mechanism has shifted regulatory enforcement from manual, experience-based practices to data-driven, intelligent regulation, offering a replicable model for technology-enabled governance.

The RMI linkage mechanism has provided precise support for Beijing's air quality management, helping to consolidate air quality gains. Beijing's annual average PM_{2.5} concentration has been lower than 35 µg/m³ for four consecutive years, with 2024 recording the highest number of good or excellent air quality days and the fewest heavy pollution days. Looking ahead, the RMI linkage model will continue to evolve through the enhanced use of big data and artificial intelligence in building an integrated technical support system—covering evaluation, diagnosis, early warning, analysis, and decision-making—which will enable intelligent analysis of pollution issues. This will further enhance the efficiency of pollution detection, analysis, and closed-loop management and drive governance toward a faster response, more accurate identification, and more stable control.

Shanghai's Industrial VOC Control: Refined Governance to Coordinately Tackle PM_{2.5} and O₃ Pollution

As one of the first cities in China to explore the control of VOCs from industrial sources, Shanghai has made sustained progress in its governance model over more than a decade. Since the census of VOC emission sources in 2007, Shanghai has expanded its governance scope from a small set of pilot enterprises to over 2,000 industrial enterprises across the city, allowing the establishment of a replicable and scalable model for the control of industrial VOCs. Key experiences summarized include:

- Combining top-level design with phased implementation.** Controlling Shanghai's VOCs began with foundational work, such as the development of an emission inventory in 2007, the launching of pilot projects in 2011, a phased citywide rollout from 2014 onward, and advancement into a deepening stage in 2020. This "pilot-first, gradual expansion" approach ensured a smooth transition from targeted control in key enterprises to full coverage across all relevant sectors.
- Advancing institutional innovation and upgrading the control model.** In 2014, Shanghai pioneered plant-specific measures to guide enterprises in developing tailored VOC emission reduction plans. Since 2020, this has evolved into sector-specific measures based on dedicated action lists—providing standardized action lists for different industries—marking a shift from customized solutions to standardized management for controlling industrial VOCs.
- Integrating policy coordination with multistakeholder engagement.** Shanghai has effectively combined positive

incentives—such as subsidies—with regulatory constraints, including pollution discharge fees and strict enforcement measures, forming a coherent and mutually supportive policy mix that encourages proactive emission reduction by enterprises and ensures the effective implementation of control measures.

- Adopting targeted measures while strengthening law-based governance.** Shanghai has developed differentiated standards and technical specifications for key industries, providing clear guidance for enterprises while prioritizing sectors with high emissions, high reactivity, and significant environmental impacts. This has enabled a classified and tiered management approach that ensures resources are directed to where they are most needed. Meanwhile, regulatory enforcement has been paired with policy interpretation and technical assistance, supporting the transition of enterprises from compliance-driven responses to proactive control.

Through sustained and systematic governance, Shanghai has significantly reduced industrial VOC emissions, playing a critical role in the coordinated control of PM_{2.5} and O₃. The annual average PM_{2.5} concentration has remained below 35 µg/m³ since 2020, and the upward trend in O₃ concentration has been curbed. Meanwhile, control over VOCs has spurred environmental investments and stimulated the growth of the environmental industry chain. Going forward, Shanghai will continue to sustain source reduction, strengthen process control to reduce fugitive VOC emissions, and advance differentiated and targeted regulations to improve end-of-pipe treatment efficiency. These efforts aim to unlock further VOC reduction potential and enable higher-level air quality improvements.

Shanghai's Intelligent Supervision of Heavy-Duty Diesel Vehicle Emissions: Digitally Empowering Refined Mobile Source Governance

As a national logistics hub, Shanghai has a vast demand for road freight, dominated by a large fleet of heavy-duty diesel vehicles (HDDVs) that generate significant emissions. To achieve centralized, real-time, and efficient regulation of HDDVs, the Shanghai Academy of Environmental Sciences spearheaded the development of an intelligent supervision system, enabling intelligent, automated pollution control across the full chain of “vehicles, fuels, roads, and enterprises,” advancing refined mobile source governance, and strengthening regulatory effectiveness. Key experiences include:

- **Building a multisource, integrated digital foundation and system architecture for real-time, round-the-clock supervision.** The system has integrated multisource big data and established advanced architecture to enable the real-time monitoring of vehicle operations and emissions citywide. It can also identify freight corridors linked to key enterprises and port terminals and is capable of dynamic emission tracking, thereby supporting targeted regulatory action.
- **Establishing algorithm-driven, full-chain supervision across vehicles, enterprises, industries, and regions.** By combining vehicle emission and fault data with real-time operational and activity data, the system applies high-emission vehicle recognition algorithms, AI-based clustering algorithms, and reverse geocoding techniques to realize the integrated

supervision of vehicles, affiliated enterprises, industries, and major vehicle users—effectively overcoming the inefficiencies and limited accuracy of traditional methods in identifying high-emission vehicles.

- **Constructing a closed-loop management system covering the full chain of “vehicles, fuels, roads, and enterprises.”** The system integrates modules for high-emission vehicle identification, non-public refueling station recognition, freight corridor detection and tracking, and major vehicle user supervision, eliminating blind spots in in-use compliance, fuel management, freight corridor monitoring and optimization, and key vehicle user oversight. It also bridges supervision needs across multiple levels, enhancing coordination and significantly improving the overall effectiveness and precision of supervision.

The system has become a key supporter in implementing diesel vehicle emission control measures, supporting the phase-out of old diesel vehicles and tracking resulting emission reductions. It has also informed Shanghai's periodic inspection exemption policy for clean diesel vehicles, with its exemption identification module launched on January 1, 2023—encouraging proper vehicle operation and reducing emissions. Going forward, Shanghai will further expand its supervision capabilities by developing new functional modules and application scenarios, such as multisource data integration, the standardized management and traceability of refueling sites, and the automated evaluation of temporary control measures and major events, continuously supporting air quality improvements.

Chengdu's Near-Zero Carbon Construction Site Pilot: Scenario-Based Exploration for Synergistic Pollution Mitigation and Decarbonization

To target construction sites as a key intervention for reducing emissions from major sources—mobile vehicles and fugitive dust—Chengdu launched a near-zero carbon construction site pilot, promoting the replacement of conventional equipment with new energy equipment and incorporating low-carbon practices throughout the construction process. This approach accelerates decarbonization in the construction sector and provides a scalable model for sustained air quality improvement and coordinated pollution-carbon reduction. Key experiences include:

- **Establishing a “government-led, enterprise-implemented, third-party verified” collaborative mechanism.** The Chengdu Municipal Bureau of Ecology and Environment (CMBEE) lead pilot design and implementation planning, working with relevant agencies through a multidepartment, multilevel coordination mechanism. The construction contractor assumes responsibility for on-ground implementation, while a third-party agency conducts monitoring and evaluation—ensuring clear roles and streamlined responsibilities among all parties.
- **Advancing new energy equipment adoption through a pronged approach.** The CMBEE has engaged with several manufacturers to conduct technical matching studies of new energy machinery while introducing a series of support measures, such as

establishing dedicated charging channels for new energy heavy-duty trucks, coordinating temporary sites to install charging facilities, and tailoring grid capacity to meet the pilot projects' electricity demand. In parallel, the pilot incorporated enhanced fugitive dust control, green construction practices, and whole-process management to improve both operational efficiency and emission reduction performance during the construction phase.

- **Strengthening intelligent monitoring to enable whole-process management and inform decision-making.** The pilot built an intelligent carbon monitoring platform, established a closed-loop “monitoring-verification-optimization” system for the precise, real-time tracking of construction data, and engaged third-party verification to ensure data transparency, authenticity, and traceability—altogether providing a solid foundation for scientific decision-making and continuous management optimization.

Chengdu's pilot project has delivered both environmental and social gains. Emissions of SO₂, NO_x, PM₁₀, PM_{2.5}, and CO₂ have dropped significantly, while the pilot has accelerated the construction sector's green transition, improved living conditions for nearby residents, and generated new jobs alongside enhanced workforce skills. In the future, Chengdu will further expand the deployment of new energy equipment to meet diverse construction needs, build on pilot experience to gradually extend the model to other types of sites, and develop differentiated evaluation standards to guide wider application.





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BTH REGION

A Pathway to Regional Cleaner Air:

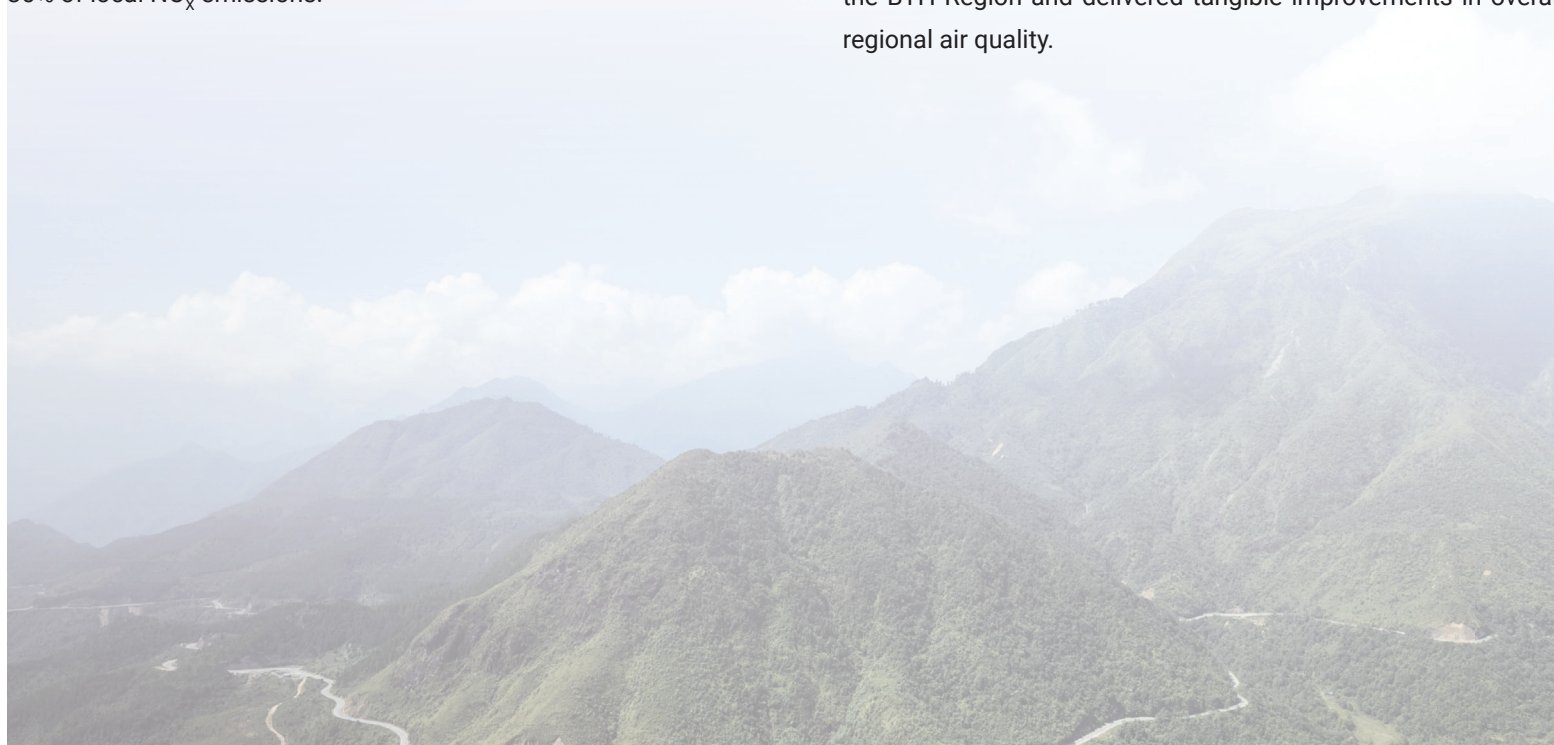
Joint Prevention and Control in the Beijing–
Tianjin–Hebei and Surrounding Areas

1. Background

The Beijing–Tianjin–Hebei and surrounding areas (the BTH Region) have experienced rapid economic growth and surging energy demand, yet the region still features a heavy industrial base, coal-dominated energy use, and road-based freight—structural factors that put sustained pressure on air quality improvement. Hebei Province is illustrative; in 2023, its secondary industry accounted for about 37% of GDP—well above the national average of 23%—with energy-intensive sectors such as steel and petrochemical playing major roles. Coal remains the mainstay of energy consumption (around 80% in 2020). Road freight also dominates, with over 80% of bulk goods transported by trucks, leading heavy-duty diesel vehicles to contribute over 30% of local NO_x emissions.

Geographic and meteorological factors compound the challenge. The region's semi-enclosed topography limits atmospheric dispersion. Moreover, the region often shares the same airflow system; under southerly winds, pollutants readily accumulate and are transported across provincial boundaries. Under such circumstances, city-by-city measures alone are insufficient, underscoring the need for regional joint prevention and control of air pollution.

Recognizing these realities, the central government has prioritized regional joint prevention and control, establishing an integrated framework that has strengthened air pollution governance across the BTH Region and delivered tangible improvements in overall regional air quality.



2. Evolution

The joint prevention and control of air pollution in the BTH Region began with the coordinated air quality measures implemented during the 2008 Beijing Olympic Games. The mechanism was later reinforced during major events, such as the 2014 Asia-Pacific Economic Cooperation (APEC) Leaders' Meeting, the Grand Rally to Celebrate the 70th Anniversary of the Founding of the People's Republic of China, and the 2022 Beijing Winter Olympics. As practices advanced, the regional scope of joint prevention and control gradually expanded to the "2 + 36" cities (Figure 1-1), forming an integrated regional governance structure. The overall evolution can be summarized in three stages.

a) Stage I (before 2013)

In 1998, the Beijing Municipal Government issued its first emergency notice on air pollution control, marking the start of the city's proactive efforts. Under the 2000 revision of the *Law of the People's Republic of China on the Prevention and Control of Atmospheric Pollution*, it was for the first time stipulated that, when air pollution becomes severe and endangers public health and safety, the local government shall promptly issue a public announcement to residents and adopt compulsory emergency measures. However, the law did not establish a separate chapter on responses to heavy pollution and lacked detailed

implementation provisions; consequently, the early phase of regional joint prevention and control primarily served the purpose of safeguarding air quality during major events.

In 2008, to ensure clean air for the Beijing Olympic and Paralympic Games, a package of measures was implemented in Beijing, Tianjin, Hebei, Shanxi, Inner Mongolia and Shandong, including vehicle restrictions, the suspension of construction activities, production curtailment at key enterprises, emission reduction requirements for coal-fired facilities, the control of volatile organic compounds (VOCs), and emergency responses under extremely unfavorable meteorological conditions. These emission control measures led to a significant decrease in air pollutants, accounting for 71% and 60% of the reductions in PM_{10} and $PM_{2.5}$ concentrations, respectively, positioning them as the principal contributors to improved air quality.

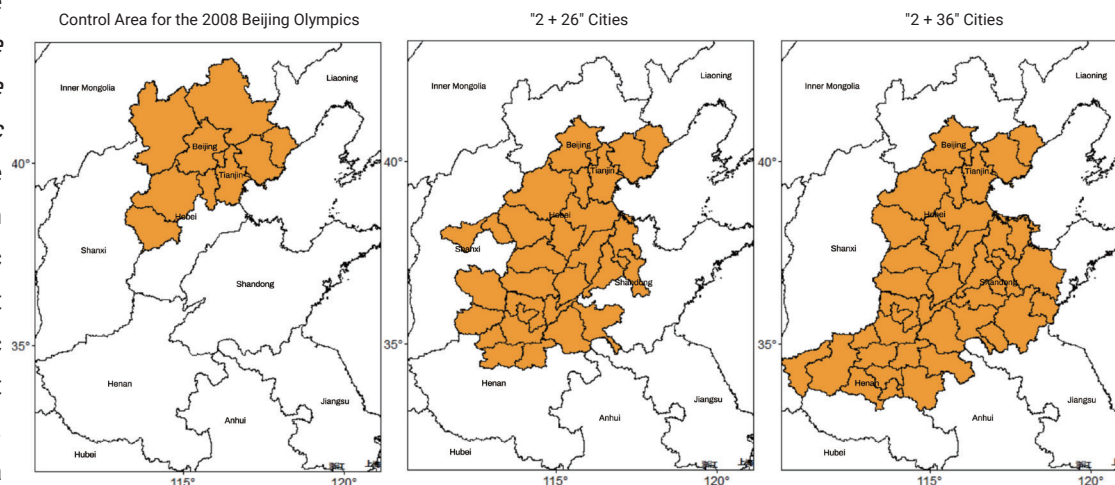


Figure 1-1 Expansion of Regional Joint Prevention and Control Areas (2008 to Present)

b) Stage II (2013–2022)

In early 2013, a severe air pollution episode in the BTH Region drew nationwide attention. In September, the State Council issued the *Action Plan on the Prevention and Control of Air Pollution*, which called for the establishment of regional joint prevention and control mechanisms in the BTH Region. These mechanisms involved provincial-level governments and relevant State Council departments—such as the former Ministry of Environmental Protection and the China Meteorological Administration—to address cross-regional pollution challenges, coordinate air pollution control measures, and report progress, thereby laying the institutional foundation for joint prevention and control.

The effectiveness of joint prevention and control was initially demonstrated during major national events such as the 2014 APEC Leaders' Meeting and the 2015 military parade. During the APEC meeting in November 2014, six provincial-level regions—Beijing, Tianjin, Hebei, Shanxi, Inner Mongolia, and Shandong—jointly implemented strict emission reduction measures targeting coal combustion, vehicles, industry, and fugitive dust. As a result, from November 1–12, 2014, concentrations of key pollutants—including $PM_{2.5}$, PM_{10} , SO_2 , and NO_2 —in Beijing dropped to their lowest levels in the last five years; $PM_{2.5}$ concentrations alone fell by 54.5% year-on-year for the same period.

In 2018, the State Council issued the *Three-Year Action Plan for Winning the Blue Sky Defense Battle*, further refining the regional coordination framework and specifying the BTH Region as the “2 + 26” cities. The plan strengthened the joint emergency response to heavy pollution episodes by requiring unified alerts and synchronized emission reduction measures across cities based on alert level. It also set the emission reduction targets—in principle, not lower than 10%, 20%, and 30% for yellow, orange,

and red alerts, respectively—and applied differentiated control measures based on enterprises' environmental performance ratings.

During the 2022 Beijing Winter Olympic Games (February 4–20), the Ministry of Ecology and Environment (MEE), in coordination with local governments in the BTH Region, implemented targeted regional joint prevention and control measures. Temporary control measures were applied to selected enterprises and vehicles with high emissions but relatively minor economic impact, with actions specified at the level of enterprises, production processes, equipment, and vehicles, further improving air quality. Comprehensive assessments indicate that, during the Games, regional pollutant emissions declined by over 30%; the average $PM_{2.5}$ concentration in the BTH Region fell by 20% year-on-year; and the number of heavy pollution days decreased by more than 90%.

c) Stage III (since 2023)

Recognizing that the “2 + 26” cities did not fully cover key cities along the pollution transport corridor, the *Action Plan for the Sustained Improvement of Air Quality*, issued by the State Council in 2023, formally expanded the BTH Region to “2 + 36” cities. In addition, to effectively offset the impact of extremely unfavorable meteorological conditions during autumn–winter seasons, the MEE launched multiple rounds of proactive, regional coordinated emergency responses targeting prolonged and wide-area heavy pollution episodes in autumn–winter 2024–2025. These joint actions extended beyond the BTH Region, to include the Yangtze River Delta (YRD) Region, the Fenwei Plain, and the urban agglomeration in the middle reaches of the Yangtze River, thereby mitigating pollution accumulation in the BTH Region and reducing the frequency of heavy pollution episodes in central and eastern China.

3. Framework

To ensure the effective implementation of joint prevention and control, the BTH Region has gradually developed a multi-level coordinated governance system and formed mechanisms for inter-regional and cross-sectoral collaboration.

a) Multi-Level Governance Structure

In 2018, the State Council established the Leading Group for Air Pollution Prevention and Control in the BTH Region, comprising leaders from 13 ministries and 7 provincial-level governments. The group is responsible for setting regional air quality targets, reviewing major policies, and coordinating cross-provincial issues. Meanwhile, the MEE also assumed responsibilities for daily monitoring and forecasting, managing emergency response lists, and dispatching cross-regional law enforcement, thereby institutionalizing and mainstreaming regional coordination.

b) Inter-Regional and Cross-Sectoral Collaboration

Inter-regional collaboration has driven unified planning and environmental standards. The National Development and Reform Commission (NDRC), the MEE, and other central departments jointly developed regional ecological and environmental protection plans. Beijing, Tianjin, and Hebei aligned their legislative efforts to adopt unified regulations—such as the

Regulations on the Prevention and Control of Pollution from Motor Vehicles and Non-Road Mobile Machinery—and jointly issued regional environmental standards, while also implementing emission limits in key areas that are more stringent than national standards.

Cross-sectoral collaboration also advanced structural adjustments and emission reduction actions. The Ministry of Industry and Information Technology, the NDRC, and the MEE jointly promoted the phase-out of outdated production capacity and the rectification of small, scattered, and polluting enterprises, while imposing strict controls on new high-emission industrial projects in the BTH Region. The National Energy Administration and the NDRC led efforts to reduce coal consumption and accelerate clean energy substitution. Meanwhile, the Ministry of Transport and the MEE jointly advanced transportation restructuring initiatives, implemented more stringent vehicle emission standards, and promoted the large-scale adoption of new energy vehicles (NEVs^[1]), reducing emissions at the source.

^[1] In China's policy context, NEVs refer primarily to battery electric vehicles, plug-in hybrid electric vehicles, and fuel cell vehicles.

4. Supporting Measures

Both national and local governments have provided comprehensive support across multiple dimensions—including technology, funding, regulatory standards, and heavy pollution emergency response systems—thereby reinforcing the institutional foundation for advancing regional joint prevention and control.

a) Technical Support Systems

For industrial sources, the *Project on the Causes and Control of Heavy Air Pollution* has facilitated technological advancements, including ultra-low-emission retrofits in major industries, the substitution of raw and auxiliary materials with low-VOCs content, and the transition to clean energy in industrial furnaces.

For mobile sources, efforts have centered on digital regulation, source-based emission reduction, and technological upgrades. Key measures include enhancing remote on-board emissions monitoring systems for heavy-duty vehicles and non-road mobile machinery; tightening vapor recovery across fuel storage, transport, and marketing; promoting access-control video monitoring systems for enterprises with high transport volumes; and guiding third-party emission inspection agencies to apply big data and AI to improve regulatory efficiency and precision.

For area sources, efforts to reduce fugitive dust and ammonia emissions have been actively promoted. Enclosure retrofits have been advanced for dust-control facilities at mines and bulk cargo terminals and for material conveying systems. Innovative

technologies, such as air-membrane canopies installed over excavation pits, have been introduced to further suppress dust. In addition, ammonia emission reduction has been promoted through pilot programs that encourage the deep application of nitrogen fertilizers and the adoption of low-protein feed technologies.

In addition, the BTH Region has continued to promote intelligent regulation, which helps address complex pollution sources and cross-regional transport, provides scientific decision-making support for emergency emission reduction, and enhances the overall effectiveness of air quality management.

b) Heavy Pollution Response System

China has developed a comprehensive heavy pollution response system that integrates monitoring and forecasting, source analysis, early warning, emergency response, performance evaluation, and public communication.

For monitoring and forecasting, the BTH Region established a four-tier forecasting system—covering national, regional, provincial, and city levels—which now provides accurate 7–15-day air quality forecasts and 45-day extended-range forecasts, significantly strengthening the forecasting capabilities for heavy pollution events.

For source analysis, scientific research initiatives—such as the *Project on the Causes and Control of Heavy Air Pollution*—have

clarified the causes of autumn–winter heavy pollution in the BTH Region from four perspectives: pollutant emissions, chemical transformation, meteorological variability, and pollution transport.

For early warning and emergency response, the central government has introduced a list- and performance-based emergency emission reduction system, promoting differentiated and precise control. The compilation of emergency emission reduction lists has been continuously refined, and the number of enterprises covered has increased rapidly. By 2024, the lists covered all cities that had experienced heavy pollution episodes, spanning 29 provincial-level regions.

For performance tracking and evaluation, advanced technologies—including near-real-time emission characterization, high-resolution remote sensing, and mobile monitoring—have been integrated to markedly enhance intelligent remote supervision of emission sources, real-time characterization of society-wide emissions, and comprehensive assessment of control measure effectiveness, thereby achieving a regulatory closed loop of problem identification, joint evaluation, and local rectification.

For public communication, communication mechanisms have been strengthened to enhance policy transparency and build public support. During heavy pollution episodes, expert commentaries are organized to respond to public concerns, guide public perception, and foster broad social participation.

c) Financial Incentives Mechanisms

The BTH Region has progressively established an environmental economic policy framework that combines multiple instruments—

including subsidies, fees, rewards, pricing policies, and financial tools—to support the control of major air pollution sources, such as coal combustion, motor vehicles, and industrial emissions.

For coal combustion, local governments have allocated fiscal funds to support the clean energy retrofitting of coal-fired boilers, the replacement of scattered coal use in urban and rural households, and the implementation of coal-to-electricity or coal-to-gas programs in rural areas. In Beijing, for instance, households completing clean energy retrofits are eligible for discounted heating electricity tariffs, with reductions exceeding 60%.

For vehicle emissions, fiscal subsidies have been introduced to phase out old and high-emission vehicles, strengthen emission controls for heavy-duty diesel trucks, and promote the adoption of NEVs. In many cases, local governments provide additional subsidies on top of central incentives for eligible NEV purchases.

For industrial pollution, a mix of subsidies, reward mechanisms, and differentiated pollution discharge fees have been implemented to promote the phase-out of high-pollution enterprises and the transition towards cleaner production. Enterprises that voluntarily shut down heavy-polluting production lines or fully exit production may receive financial incentives of up to several million yuan.

d) Legal and Standard Framework

Significant progress has been made in strengthening the legal foundation, regulatory system, and environmental standards that underpin regional joint prevention and control.

For legal and regulatory development, the 2015 revision of the

Law of the People's Republic of China on the Prevention and Control of Atmospheric Pollution (hereinafter referred to as the "Air Pollution Prevention and Control Law"), legally established mechanisms for regional joint prevention and control and for responses to heavy pollution episodes. The *Three-Year Action Plan for Winning the Blue Sky Defense Battle* further designated the BTH Region as a key region, promoting coordinated emission reduction and emergency response. In parallel, multiple provincial-level jurisdictions in the region jointly revised their local air

pollution control regulations to define legal responsibilities and coordination mechanisms for regional joint governance.

For standard harmonization and upgrading, Beijing, Tianjin and Hebei jointly issued their first unified environmental standard in 2017, setting limits on VOC content in architectural coatings and adhesives. Since then, coordinated standard-setting has expanded to key sectors such as steel production, fuel quality, vehicle emissions, and boiler atmospheric pollutants.



5. Outcomes

Since 2013, the emissions of major air pollutants in the BTH Region has continued to decline, achieving a win-win outcome of economic growth and improved air quality.

The concentration of major air pollutants in the BTH Region has fallen sharply, with PM_{2.5} showing the most substantial reduction (Figure 1-2). By 2024, the annual average PM_{2.5} concentrations in Beijing, Tianjin, and Hebei had decreased to 30.5 µg/m³, 38.1 µg/m³, and 37.7 µg/m³, respectively—all down by approximately 60% from 2013 levels. O₃ levels have also been brought under control. In Beijing, for example, the 90th-percentile daily maximum 8-hour

average O₃ concentration in 2024 was 6.8% lower than in 2013, indicating that the previous upward trend has been largely curbed and that initial progress has been made in the synergistic control of PM_{2.5} and O₃ pollution.

With pollutant concentrations declining, overall air quality has improved substantially. Beijing saw particularly notable improvements: Good or excellent air quality days rose to 290, with a proportion of 79.2%, and heavy pollution days dropped from 58 in 2013 to just 2 in 2024. Similar improvements were observed in Tianjin and Hebei, where heavy pollution days fell by 45 and 75, respectively.

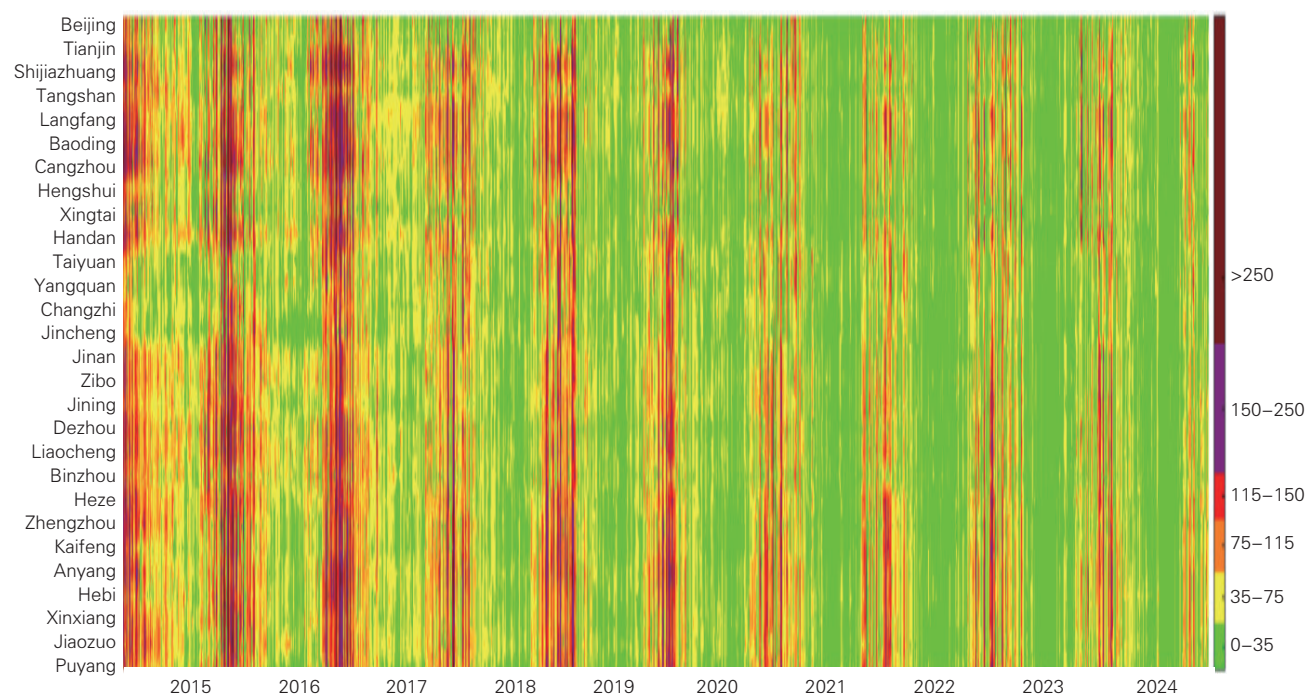


Figure 1-2 PM_{2.5} Concentration Trends in the “2 + 26” Cities (2015–2024)

Regional joint emergency response measures have yielded significant results. Between October and December 2024, the BTH Region experienced four pollution episodes and activated joint emergency response actions, alongside simultaneous emission reduction actions in other key regions, including the YRD Region and the urban agglomeration in the middle reaches of the Yangtze River, achieving strong overall effectiveness.

Despite a notable increase in power generation and heating demand, online emissions monitoring data showed reductions of 16%–31% from key pollution sources. During pollution episodes, the BTH Region recorded 119 moderate-to-heavy pollution days—373 days fewer than forecasts under a no-response scenario (Figure 1-3).

"2 + 36" Cities		20241023		20241024		20241025		20241026		20241027		20241028		20241029		20241030		20241031		20241101		20241102		20241103	
		Pre	Obs	Pre	Obs	Pre	Obs	Pre	Obs	Pre	Obs	Pre	Obs	Pre	Obs	Pre	Obs	Pre	Obs	Pre	Obs	Pre	Obs	Pre	Obs
Beijing		43-59	22	67-83	43	91-107	115	108-122	153	21-35	11	51-67	23	75-91	68	51-67	67	67-83	104	67-83	99	108-122	92	35-51	43
Tianjin		47-71	45	67-91	92	99-122	109	107-129	128	55-79	68	83-107	45	99-122	86	63-87	66	83-107	100	51-75	70	83-107	81	43-67	46
Hebei Province	Shijiazhuang	67-91	31	91-115	64	136-160	114	129-150	153	99-122	75	99-122	46	136-160	98	136-160	106	136-180	83	122-143	50	136-160	51	75-99	65
	Tangshan	57-81	37	79-103	84	95-118	106	115-136	98	43-67	60	91-115	57	111-132	75	71-95	46	95-118	83	39-63	79	67-91	33	95-118	42
	Langfang	59-83	47	95-118	95	118-139	112	139-165	160	91-115	41	95-118	55	136-160	90	107-129	92	111-132	100	103-125	93	132-155	66	99-122	38
	Baoding	63-87	37	95-118	74	132-155	113	136-160	158	111-132	77	111-132	48	132-155	91	132-155	107	132-155	97	111-132	57	132-155	57	63-87	55
	Cangzhou	67-91	50	103-125	72	103-125	90	136-160	123	83-107	66	99-122	29	150-200	94	103-125	141	136-160	133	99-122	48	136-160	60	99-122	82
	Hengshui	67-91	50	95-118	83	139-165	79	136-180	99	103-125	88	103-125	38	132-155	96	139-165	153	136-180	155	122-143	53	132-155	49	67-91	92
	Xingtai	59-83	31	122-143	68	132-155	89	139-185	104	122-143	100	115-136	60	132-155	111	136-160	142	136-160	112	129-150	32	136-160	46	107-129	57
	Handan	59-83	46	99-122	66	118-139	87	136-160	96	95-118	134	99-122	60	136-160	106	136-160	169	136-160	126	118-139	53	139-165	57	59-83	74
Henan Province	Qinhuangdao	59-83	32	75-99	72	111-132	70	122-143	73	43-67	33	59-83	39	95-118	68	79-103	26	95-118	58	75-99	51	75-99	24	55-79	65
	Zhengzhou	59-91	28	72-110	52	81-123	63	122-190	79	122-190	89	126-155	111	85-128	114	91-136	112	81-123	170	85-128	60	126-155	61	76-116	60
	Kaifeng	59-91	61	72-110	53	81-123	68	126-155	88	126-155	100	91-136	90	85-128	94	85-128	105	72-110	126	91-136	42	93-117	52	118-160	76
	Anyang	56-86	55	78-119	61	81-123	75	122-190	92	126-155	119	126-155	70	126-155	124	126-155	175	126-155	144	126-155	53	91-136	64	81-123	91
	Hebi	56-86	51	78-119	61	81-123	64	122-190	86	126-155	117	126-155	72	91-136	121	126-155	163	91-136	145	126-155	43	91-136	59	81-123	81
	Xinxiang	59-91	51	72-110	60	81-123	66	122-190	100	126-155	136	126-155	86	91-136	124	91-136	144	91-136	166	126-155	53	126-155	72	91-136	74
	Jiaozuo	56-86	33	72-110	54	81-123	71	122-190	90	126-155	134	126-155	94	91-136	111	91-136	128	76-116	155	126-155	57	118-160	56	76-116	50
	Puyang	59-91	61	78-119	56	81-123	70	137-171	77	126-155	96	126-155	70	91-136	98	126-155	150	107-129	160	91-136	56	95-118	64	85-128	91
	Xuchang	65-101	36	65-101	52	72-110	65	126-155	110	136-170	121	126-155	124	91-136	99	85-128	100	72-110	163	91-136	69	118-160	80	118-150	88
	Luohe	65-101	36	65-101	43	72-110	64	126-155	108	136-170	126	126-155	110	91-136	90	85-128	82	72-110	76	91-136	83	118-160	83	118-150	85
	Pingdingshan	65-101	25	65-101	46	72-110	65	126-155	67	126-155	45	126-155	113	91-136	89	85-128	83	72-110	111	91-136	88	118-160	68	76-116	64
	Shangqiu	65-101	60	49-77	50	54-83	74	91-136	67	126-155	134	91-136	112	85-128	111	85-128	101	76-116	84	81-123	132	95-118	92	126-155	98
	Zhoukou	56-86	67	49-77	44	54-83	49	91-136	89	126-155	115	126-155	96	85-128	117	85-128	75	72-110	54	76-116	87	103-140	83	118-150	86
	Sanmenxia	53-81	16	53-81	35	72-110	59	85-128	57	72-110	24	85-128	56	85-128	79	72-110	80	59-91	100	72-110	66	59-91	59	62-95	61
	Luoyang	53-81	25	56-86	48	81-123	76	76-116	60	72-110	33	126-155	114	91-136	118	85-128	125	78-119	164	78-119	64	78-119	56	75-115	54
Shandong Province	Jinan	43-67	26	55-79	41	67-91	71	67-91	67	63-87	100	55-79	23	59-83	53	64-88	103	83-107	126	95-118	77	43-67	34	63-87	61
	Zibo	55-79	28	71-95	50	95-118	73	83-107	87	55-79	81	63-87	36	71-95	58	83-107	103	87-111	132	83-107	73	63-87	56	55-79	57
	Jining	47-71	45	55-79	50	67-91	58	59-83	62	39-63	117	55-79	48	67-91	75	63-87	102	75-99	103	59-83	112	59-83	49	63-87	79
	Dezhou	59-83	50	71-95	58	83-107	83	95-118	107	55-79	88	71-95	25	118-140	79	103-126	133	107-129	159	83-107	36	53-77	47	55-79	91
	Liaocheng	61-85	51	67-91	45	91-115	67	101-123	91	83-107	91	71-95	41	103-126	82	129-150	117	103-126	144	115-136	58	115-136	46	103-126	84
	Binzhou	14-20	30	71-95	52	79-103	84	59-83	96	14-20	54	11-18	32	52-76	72	71-95	100	47-71	97	63-87	50	10-17	61	55-79	60
	Heze	59-83	61	63-87	43	95-118	67	99-122	52	95-118	82	71-95	77	71-95	109	99-122	118	111-132	115	95-118	88	111-132	64	111-132	90
	Linyi	14-20	29	67-91	54	59-83	51	18-24	33	55-79	54	52-76	23	52-76	70	67-91	94	63-87	64	10-17	37	10-15	50	13-17	90
	Taian	23-42	34	41-60	49	53-72	67	41-60	56	12-31	87	55-79	30	31-50	56	41-60	88	73-92	107	35-54	81	31-50	35	52-75	70
	Weifang	45-79	21	61-91	52	61-91	64	65-95	44	40-79	50	21-51	44	40-79	50	69-99	77	77-107	84	65-95	51	25-59	58	60-91	54
	Dongying	43-67	26	71-95	49	75-99	70	79-103	44	47-71	33	39-63	30	52-76	63	67-91	64	79-103	62	67-91	46	55-79	43	55-79	57
	Zaozhuang	47-71	36	63-87	46	55-79	47	63-87	37	55-79	80	59-83	40	59-83	52	71-95	77	59-83	68	59-83	48	55-79	56	75-99	79
	Rizhao	11-18	22	13-20	43	43-67	34	16-23	26	11-18	41	8-15	19	12-19	38	18-25	67	59-83	47	12-19	34	8-15	59	16-23	55

Obs—Observed Air Quality Pre—Forecast Air Quality

Figure 1-3 Comparison of Observed and Forecast Air Quality in the BTH Region During Heavy Pollution Episodes (October–November 2024)

6. Outlook

With air pollution control deepening, the BTH Region—despite remarkable progress—needs to continue strengthening and improving its governance systems, technical capacity, and coordination mechanisms across multiple dimensions.

a) Enhancing Forecasting and Early-Warning Capacity

Future efforts need to focus on building an autonomous, controllable system and facilitate interconnection and product sharing by data integration. First, near-real-time emission inventories need to be established, along with enhanced urban-scale meteorological forecasting and the improved monitoring and analysis of pollution-related meteorological indicators. Second, forecasting parameters should be optimized for seasonal variation, integrating machine learning to develop probabilistic, potential, and short-term forecasts. Third, a multi-tier scientific evaluation system needs to be built to assess forecast outputs, while expanding capabilities for pollution-source tracing, emission-reduction assessment, and specialized forecasts for dust storms, wildfires, and straw burning. Standardized operational procedures and personnel quality-control protocols also need to be introduced. Within the collaboration framework between meteorological and environmental authorities, efforts should be made to promote resource sharing and leverage complementary strengths.

b) Refining Emergency Emission Reduction Lists

As a core component of heavy air pollution emergency response plans, an essential basis for implementing emergency emission

reduction measures, and a key foundation for effectively responding to heavy pollution episodes, emergency emission reduction lists need to be further refined and standardized. In particular, issues such as the incomplete inclusion of air-emitting enterprises, the failure of emission reduction measures to deliver actual reductions, excessive exemptions from production curtailment or emission control requirements, and insufficient review and oversight by local authorities urgently require policy guidance from national authorities to improve the quality and consistency of list development and management. In 2025, a technical guideline was issued to support the compilation of emergency emission reduction lists for heavy pollution, outlining requirements for heavy pollution episodes, including dual reductions in pollutant emissions and production output, as well as stricter control of mobile sources.

c) Developing a Pollution Control Technology System

Progress in three areas will be critical to establishing a comprehensive pollution control technology system. The first involves developing dynamic optimization technologies by establishing quantitative response relationships among control targets, mitigation actions, and emission reduction outcomes; designing scenarios based on the spatiotemporal variation of emissions, source contributions, and meteorological conditions; and identifying optimal control pathways under the dual constraints of improving regional air quality and minimizing economic impacts. Second is advancing intelligent supervision technologies for pollution sources and developing a classified and tiered management system for pollution cases to enable

precise process control and ensure the local implementation of emission reduction responsibilities. Third is enhancing comprehensive evaluation technologies to support the real-time assessment of emission reduction performance. This involves establishing response relationships between emissions, air quality, and key pollutant components, allowing for the quantitative evaluation of the contribution of specific control measures in improving air quality.

d) Strengthening Legal Enforcement and Regulation

Stronger regulations are essential to tapping into emission reduction potential. Relevant laws should be revised to include explicit penalties for violations of heavy pollution emergency response requirements, thereby enhancing legal deterrence. A closed-loop management mechanism should be established to enable precise tracking and prompt the rectification of identified problems. Information-based regulatory capacity should be

further enhanced by moving regulatory tools onto digital platforms and leveraging technology to strengthen dynamic, whole-process monitoring and management, thereby ensuring that emission reduction responsibilities are effectively implemented and tangible results are delivered.

e) Improving Regional Collaboration Mechanisms

To further enhance the regional joint prevention and control mechanism for heavy pollution episodes, it is necessary to further strengthen the unified organization and capacity building for coordinated response to heavy pollution; deepen cross-regional emergency response collaboration across the BTH Region and nearby regions such as northern Jiangsu and northern Anhui; and systematically elevate regional joint prevention and control as well as overall emergency response capability in the BTH Region.



The background of the slide features a photograph of a traditional Chinese pavilion with multiple tiers and ornate roofs, situated on a stone platform by a body of water. The pavilion is surrounded by lush green trees. The entire image is covered with a semi-transparent blue overlay. On the left side, the large number '02' is displayed in a white, sans-serif font.

02

BEIJING'S

**Innovative Regulation-Monitoring-Inspection
Linkage Model:**

Deepening Emission Reduction Potential Through
Refined Governance

1. Background

As China's capital and a global megacity, Beijing has long led the nation in environmental governance, making air pollution control a top priority. Since the launch of the *Action Plan for Air Pollution Prevention and Control* in 2013, Beijing has achieved steady air quality improvement through structural optimization, emission control, and regional joint prevention and control. By 2024, the city's annual average $\text{PM}_{2.5}$ concentration had dropped to $30.5 \mu\text{g}/\text{m}^3$ —65.9% lower than in 2013. Meanwhile, PM_{10} , NO_2 , and SO_2 concentrations had fallen by 50.0%, 57.1%, and 88.7%, respectively, while the number of heavy-pollution days had dropped sharply from 58 to just 2.

As early as 2017, Beijing launched the *One Microgram Action*, marking the beginning of a new stage of precision air quality management, integrating science, law enforcement, and administrative measures to achieve fine-grained emission reductions measured in micrograms.

During the 14th Five-Year Plan (2021–2025), Beijing entered a more challenging stage, with the complexity and difficulty of pollution control rising exponentially. Traditional manual and experience-based analytical models could no longer meet the needs of high-frequency, dynamic decision-making in air quality management. To address this, Beijing introduced an innovative joint-action mechanism—the regulation-monitoring-inspection (RMI) linkage—effectively integrating overall planning/dispatching (regulation), perception-based initiation (monitoring), and targeted enforcement (inspection). This mechanism enhances precision, responsiveness, and coordination in air quality management, enabling accurate source identification, rapid response, and efficient control to support air pollution prevention and control in the new stage.



2. Evolution

The evolution and refinement of the RMI linkage model primarily centered on three key aspects.

a) Enhancement of the Monitoring System

As early as 1983, Beijing pioneered the establishment of China's first automatic atmospheric monitoring system, marking a historic leap from manual to automated monitoring. In 2016, a high-density citywide monitoring network was completed, and in 2018, Beijing again led the nation by developing the first remote online monitoring platform for heavy-duty diesel vehicles—ushering in the era of intelligent monitoring.

By 2022, Beijing had integrated satellite remote sensing, vehicle-mounted monitoring, the Internet of Things, and power consumption big data to create an integrated monitoring network characterized by “satellite observation, ground patrol, data networking, and electricity verification.” This milestone marked the formal transition of the city's monitoring system into a new stage of intelligent and precision-based operation.

b) Data-Driven Transformation in Governance

Beijing's atmospheric monitoring system now produces hundreds of millions of data records each day. However, traditional experience-based approaches have shown limited capacity for in-depth data mining and real-time analysis, falling short of the demands of refined governance. To address these challenges, the Beijing Municipal Ecological and Environmental Monitoring Center released the RMI linkage model in July 2024, which is

China's first large model in the field of ecological and environmental monitoring.

In February 2025, it was further upgraded through integration with DeepSeek, forming an intelligent assistant that integrates monitoring, assessment, early warning, source tracing, and analysis, thereby accelerating the shift from experience-driven to data-driven air quality management. The RMI linkage model has been fully deployed across command centers, analytical platforms, and mobile applications, achieving breakthroughs in data querying, intelligent Q&A, and diagnostic analysis.

c) Intelligent Upgrading for Precision and Efficiency

The RMI linkage mechanism was first piloted during the Beijing 2022 Winter Olympic Games. At the end of that year, Beijing launched a “1 + N” Precision Pollution Control Dispatching Platform, which enabled the intelligent detection of over 20 categories of pollution issues and established a closed-loop dispatching system featuring “two-hour feedback and four-hour resolution” for pollution response.

In 2023, the RMI linkage mechanism transitioned from a pilot practice to routine operation. Since 2024, Beijing has continued to expand environmental perception data sources and iteratively optimize algorithmic models, elevating pollution identification capability to the hourly level and improving source-tracing accuracy to over 75%. These advancements have significantly strengthened both the precision and responsiveness of governance.

3. Framework

Within the RMI linkage mechanism, the environmental regulation department serves as the “engine,” coordinating overall planning and dispatching as well as defining key tasks and priorities; the environmental monitoring department acts as the “sentinel,” identifying and analyzing problem clues; and the environmental enforcement department serves as the “iron fist,” tracing pollution sources and carrying out targeted enforcement actions. Together, they form a closed-loop governance and response system (Figure 2-1).

a) The RMI Linkage for Municipal–District Coordination

Beijing has established a comprehensive framework comprising the RMI linkage mechanism, RMI joint meeting mechanism, RMI assistance mechanism, and RMI source-tracing mechanism, enabling coordinated actions among different governance scenarios. The RMI linkage has developed a clear division of responsibilities, well-defined procedures, and smooth coordination. Problem clues and rectification tasks are now processed with daily identification and resolution. The continuous dispatch of problem clues and rectification progress has maintained strong implementation pressure, fully mobilizing districts, subdistricts (townships), and relevant departments, thereby fostering timely rectification and a cohesive citywide governance synergy.

By effectively addressing cross-departmental and cross-level coordination challenges, the RMI linkage—guided by precise data analysis—has driven the formation of a new governance model characterized by data-driven regulation and coordinated RMI action. This shift from fragmented operations to systematic

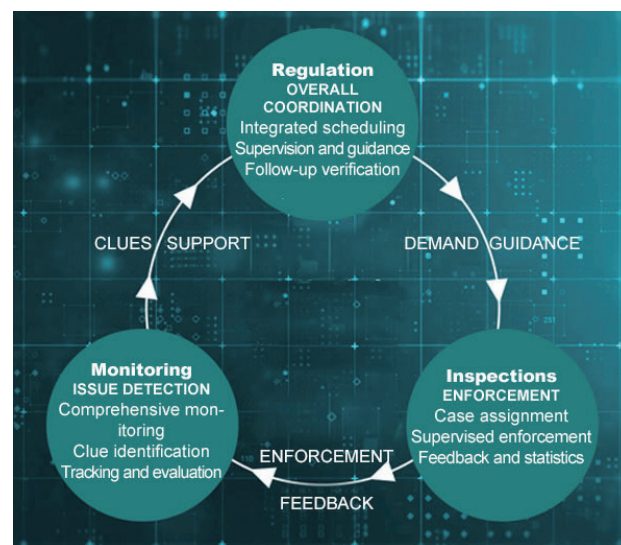


Figure 2-1 Framework of the RMI Linkage Mechanism

management, as well as from experience-based decisions to intelligent policymaking, has provided a solid institutional and technical foundation for continued air quality improvement.

b) Pre-, During-, and Post-Event Precision Management

Beijing has built a precision management framework that spans pre-event forecasting, during-event source tracing and real-time control, and post-event evaluation.

Pre-event: A multi-scale prediction system has been established—ranging from medium- and long-term forecasts to hourly predictions. Powered by artificial intelligence (AI), it enables hour-level risk alerts, supporting the transition from passive response to proactive, targeted regulation.

During event: Beijing has developed dynamic models for tracing high-value anomalies, excess emissions, and regulatory violations. For instance, a remote online monitoring system tracks the routes and emission performance of citywide heavy-duty diesel vehicles; when excessive emissions are detected, vehicle data and leads are automatically sent to enforcement departments for rapid, targeted action. Electricity-use monitoring covers key air-emitting enterprises and monitoring points, and discrepancies—such as operating production equipment without corresponding pollution-control operation—are automatically flagged. In addition, intelligent image analysis technology processes video data from tens of thousands of cameras across construction sites to identify environmental violations in real time.

Post-event: Drawing on multi-source perception data, Beijing tracks changes in emission sources, evaluates the implementation and effectiveness of control measures, and quantifies emission reduction outcomes. Systematic evaluations identify the key factors contributing to air quality improvement and assess the synergistic effects of different measures, providing a scientific basis for future policy decisions.

c) Large Model-Based Intelligent System

The RMI linkage model is developed on the foundation of general-purpose large models such as Tongyi Qianwen and DeepSeek. It is further enhanced through the integration of domain-specific atmospheric knowledge, local monitoring data, and the construction and training of thought chains (Figure 2-2).

Building upon a general knowledge base, a professional knowledge base has been established, incorporating over 1,600 items of practical and operational experience to form a structured knowledge system for precision air pollution control. This endows the model with deeper professional expertise and stronger domain adaptability. In addition, expert experience has been converted into more than 50 concrete thought chains across five key scenarios—evaluation, diagnosis, early warning, analysis, and decision-making—greatly enhancing the model's reasoning intelligence.

To objectively assess the model's performance, an evaluation dataset for precision pollution control scenarios was developed, allowing the multidimensional testing of the model's accuracy and domain expertise, supporting its continuous optimization and iteration.



Figure 2-2 Schematic Diagram of the RMI Linkage Dispatch Platform for Precision Air Pollution Control

4. Outcomes

Since 2022, the refined governance model enabled by the RMI linkage has provided strong, targeted support for Beijing's air pollution control efforts. To date, the system has achieved the closed-loop management of more than 17,000 environmental problem clues, with an issue verification rate of around 80%. Management timeliness has improved at the hourly level, and the share of off-site supervision has risen to 50%.

a) Supporting Routine Management and Emergency Response

During routine supervision and pollution episodes, the RMI linkage mechanism and its supporting technologies enable the dynamic forecasting of pollution processes, informed emission reduction decision-making, the targeted identification and dispatch of problem clues, citywide precision scheduling and enforcement, and the real-time evaluation of measure implementation. This integrated system delivers refined monitoring, scientific source tracing, precise analysis, and efficient enforcement. Assessment results show that after activating the RMI linkage and implementing emission-reduction measures, actual pollution levels dropped by one severity grade compared with a no-control scenario—demonstrating its critical role in mitigating and slowing peak pollution episodes.

b) Empowering Off-Site Supervision

The RMI linkage model integrates data on air quality, emission sources, and socioeconomic activities, enabling the precise identification of areas and sources impacting air quality. This not only strengthens oversight by ensuring that enterprises assume their emission control responsibilities but also reduces unnecessary interference with compliant enterprises, thereby improving the overall business environment.

For example, in regulating fugitive VOC emissions, monitoring departments once struggled to locate high-concentration areas. By integrating historical data with enterprise production information, mobile monitoring routes are now precisely planned to ensure the comprehensive coverage of key regions and sites. When a hotspot is detected, enforcement officers conduct immediate on-site inspections and use portable devices to locate the emission source, achieving simultaneous monitoring, investigation, and enforcement. This approach has greatly enhanced both regulatory efficiency and pollution source management.

5. Outlook

Beijing's air quality improvement has entered a new phase—aiming for a qualitative leap in $PM_{2.5}$ reduction, from around $30 \mu\text{g}/\text{m}^3$ to $20 \mu\text{g}/\text{m}^3$. In January 2025, the city launched the “0.1 Microgram Campaign” to mark this new stage of precision air quality management. Building on the steady attainment of $PM_{2.5}$ standards, the next phase of work will focus on the targeted control of key regions, critical time periods, and major emission sources, with heightened emphasis on problem identification, risk early warning, and dynamic response. As the intelligent hub of this system, the RMI linkage will further strengthen Beijing's command and dispatch capacity, intelligent monitoring capability, and off-site supervision efficiency, thereby providing strong support for science-based decision-making and precision environmental management.

To further strengthen Beijing's capacity for precision prevention and smart decision-making in air pollution control, big data and AI will be leveraged to build an integrated technical support system covering evaluation, diagnosis, early warning, analysis, and decision-making. This intelligent and accessible system will enable automated reasoning in air quality management and provide comprehensive technical support for the 0.1 Microgram Campaign.

Building on the RMI linkage, Beijing will take air quality management as an entry point to promote the coordinated control of air, water, soil, and solid waste pollution, thereby driving overall improvement in environmental quality. The RMI linkage will further enhance problem detection efficiency, analytical accuracy, and closed-loop management, enabling faster, more accurate, and more stable pollution control.

Beijing will also accelerate the modernization of its environmental monitoring system and strive to become a national pioneer in digital and intelligent transformation. Guided by innovation and practical application, Beijing will create a demonstration model characterized by technological breakthroughs, scenario-based implementation, and experience-sharing.



A background image of the Shanghai skyline, featuring prominent skyscrapers like the Shanghai Tower, Jin Mao Tower, and Shanghai World Financial Center. The sky is a clear blue.

03

SHANGHAI'S

Pioneering Paradigm for Industrial VOC Control:
Driving the Coordinated Governance of Ozone and PM_{2.5}

1. Background

Shanghai, as the core city of the Yangtze River Delta region and one of China's leading industrial hubs, exhibits a typical pattern of compound pollution driven by both PM_{2.5} and O₃ emissions. While PM_{2.5} concentrations in the city have continued to decline in recent years, O₃ pollution has remained prominent and become the primary factor constraining further air quality improvement. Between 2020 and 2024, O₃ was the primary pollutant in 66.4% of the total pollution days (Figure 3-1).

Volatile organic compounds (VOCs), a key precursor to both O₃ and secondary organic aerosols in PM_{2.5}, are therefore central to addressing complex air pollution. Studies show that industrial sources contribute nearly 70% of Shanghai's total VOC emissions, with the petrochemical sector and solvent-related industries each accounting for around one-third. This emission profile underscores that strengthening VOC control from industrial sources is essential for synergistically controlling PM_{2.5} and O₃ and is a critical pathway for achieving sustained improvements in air quality.

Since 2013, Shanghai has carried out systematic efforts to address VOC emissions from industrial sources. By establishing and refining a local legal and regulatory framework, strengthening fiscal and tax incentives, and innovating precision management through plant-specific measures, Shanghai has completed two rounds of industrial VOC emission control. These efforts have enabled the city to progress from establishing a basic system to advancing toward refined and targeted control—creating a comprehensive pathway for VOC governance that has evolved from “initial establishment” to “precision enhancement.”

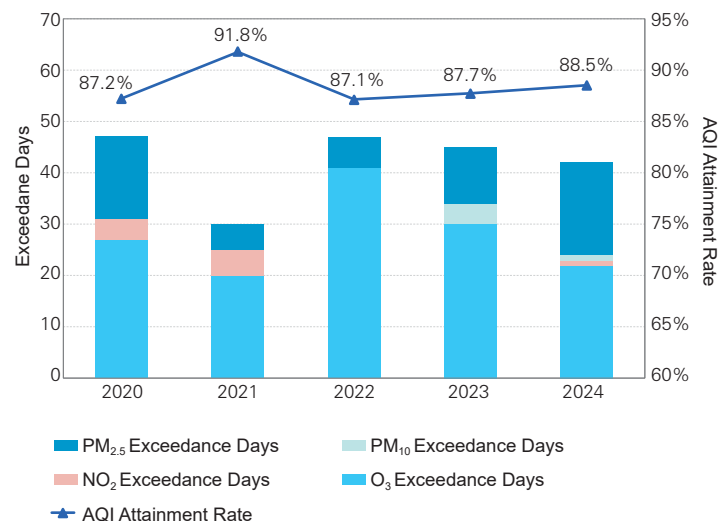


Figure 3-1 Changes in Shanghai's Air Quality Index (AQI) Attainment Rate and Proportion of Primary Pollutants on Polluted Days, 2020–2024

Note: The AQI is calculated in accordance with China's Ambient Air Quality Standards (GB 3095–2012). The AQI attainment rate refers to the percentage of days when AQI ≤100, meeting the national Class II standard: O₃ (8-hour maximum) ≤160 µg/m³, NO₂ (24-hour average) ≤80 µg/m³, PM₁₀ (24-hour average) ≤150 µg/m³, and PM_{2.5} (24-hour average) ≤75 µg/m³. A “pollutant exceedance day” is defined as a day when a pollutant is identified as the primary pollutant and the AQI exceeds 100.

2. Evolution

Shanghai's efforts to control industrial VOC emissions have progressed in a phased and continuous manner and can be broadly divided into three stages.

a) Stage I (2007–2013)

Shanghai was one of the earliest cities in China to begin controlling VOC emissions from industrial sources. In 2007, during the First National Census on Pollution Sources, Shanghai took the initiative to include VOCs in the scope of the census and, on this basis, established a relatively comprehensive emissions inventory for industrial VOCs, laying a solid foundation for scientific management in subsequent years.

In 2011, the Shanghai Municipal Bureau of Ecology and Environment (then the Shanghai Environmental Protection Bureau, hereinafter referred to as the SMBEE) issued an implementation program to pilot VOC control in key petrochemical enterprises and industrial parks. The program explored control pathways in two priority areas. The first focused on startup, shutdown, and maintenance processes in petrochemical enterprises, requiring pilot enterprises to strengthen production management, minimizing unplanned shutdowns, and reducing VOC emissions. The second targeted equipment component leaks, requiring part pilot entities to take the lead in launching leak detection and repair (LDAR) pilots. This made Shanghai the first city in China to implement systematic VOC leak control,

significantly advancing the application and promotion of LDAR and other advanced technologies nationwide.

b) Stage II (2013–2017)

Building on earlier pilot efforts, Shanghai launched the first phase of its industrial VOC control (referred to as VOC Control 1.0), gradually establishing a comprehensive governance system characterized by a focus on key industries, supported by economic incentives, and grounded in regulatory management.

In March 2014, the SMBEE issued a notice requiring 150 key industrial enterprises across the city to develop plant-specific measures for VOC reduction and complete control tasks by the end of 2015. In July 2015, the SMBEE, together with the Shanghai Municipal Development and Reform Commission (SMDRC) and the Shanghai Municipal Finance Bureau (SMFB), jointly issued two policy documents—the *Shanghai Program for Industrial VOC Control and Reduction* and the *Special Financial Support Measures for Industrial VOC Control Projects*, expanding the scope of VOC control from the initial 150 pilot enterprises to over 2,000 industrial enterprises and establishing dedicated funds to provide financial support for eligible projects. To ensure effective implementation, the SMBEE, in March 2016, issued detailed implementation rules for special financial support, further clarifying the scope of subsidies, application procedures, eligibility criteria, on-site verification requirements, and subsidy

determination standards and providing differentiated subsidies for LDAR, end-of-pipe treatment, and online monitoring projects that were implemented on schedule.

By the end of 2017, a total of 2,026 industrial enterprises had completed VOC control tasks, achieving a reduction of approximately 100,000 tons of VOCs—exceeding the phased reduction targets.

c) Stage III (2020 onward)

In early 2020, Shanghai launched a new phase of industrial VOC control—known as VOC Control 2.0—placing greater emphasis on targeted, science-based, and law-based pollution control, promoting a full-process approach that integrated source prevention, process control, and strict end-of-pipe treatment. The governance model shifted from plant-specific measures to a more systematic approach with sector-specific measures based on dedicated action lists, marking a transition toward more refined VOC control.

In 2021, in response to the combined challenges of a global economic downturn and the COVID-19 pandemic, the SMBEE, together with relevant departments, introduced a new round of special financial support. Subsidies were directly linked to actual emission reductions, with priority given to three categories of projects: source reduction projects that cut emissions through product substitution, process optimization, or equipment upgrades; process control projects that reduced fugitive emissions by improving gas-liquid balance and enhancing sealing; and end-of-pipe treatment projects that achieved deep emission reductions through enclosed collection systems and strengthened operation and maintenance. In November 2021, the SMBEE issued a detailed implementation plan to guide comprehensive VOC control in key industries, specifying timelines, requirements for calculating emission reductions, and reporting obligations, thereby providing a clear road map for the orderly advancement of VOC Control 2.0.



3. Framework

Shanghai has gradually established a well-defined and robust implementation mechanism with clear responsibilities and pathways, supported by strong institutional safeguards. This mechanism is characterized by multi-agency coordination, phased implementation, and policy guidance.

a) Multi-Agency Organizational Support

At the municipal level, the SMBEE plays a leading role and is responsible for overall planning, policy formulation, and unified oversight. The SMDRC aligns industrial policies and incorporates VOC control requirements into relevant industrial development plans, while the SMFB ensures dedicated financial support for VOC control projects. At the district level, local ecology and environment departments act as regulatory authorities, responsible for policy dissemination, technical guidance, and routine supervision within their jurisdictions. Enterprises, as the primary entities responsible for pollution control, are required to develop and implement VOC control plans and ensure stable compliance with emission standards. Technical support institutions, such as the Shanghai Academy of Environmental Sciences, provide end-to-end technical assistance, including policy and standard research, enterprise-level technical guidance, and the evaluation of control effectiveness. In addition, industry associations play an active role in organizing technical exchanges and capacity-building activities.

b) Phased and Progressive Implementation

Shanghai has adopted a phased approach to advancing VOC

control in a systematic and increasingly refined manner. During VOC Control 1.0, a “pilot-first, scale-up later” model was implemented, starting with 150 enterprises and gradually expanding to more than 2,000 enterprises citywide. In VOC Control 2.0, the scope of control was further expanded to cover 24 key industries, four general processes, and one typical emission process (odor emissions). Both phases followed a standardized implementation process consisting of setting control targets, developing control plans, conducting technical evaluations, and implementing engineering measures, ensuring that progress was scientifically guided and effectively executed.

c) Combined Approach of Incentives and Constraints

In advancing VOC control, Shanghai has adopted a combined policy approach that applies both incentives and regulatory constraints to encourage and compel enterprises to reduce emissions. During VOC Control 1.0, policies focused on differentiated support for control actions. On the incentive side, subsidies were provided for LDAR, end-of-pipe treatment, and online monitoring projects, with a maximum subsidy of CNY 10 million per enterprise. On the constraint side, a VOC pollution discharge fee was implemented, with the fee rate gradually increased from CNY 10–CNY 20 per kilogram. In VOC Control 2.0, the policy focus shifted toward performance-based outcomes. The incentive mechanism was adjusted so that subsidies were directly linked to verified VOC emission reductions, at a rate of CNY 100,000 per ton, without differentiating by project type. This shift placed greater emphasis on actual control outcomes and significantly enhanced enterprises' motivation to pursue deep emission reductions.

4. Supporting Measures

Shanghai's industrial VOC control has been driven by a comprehensive set of core measures, including legal and regulatory safeguards, science-based technical standards, a portfolio of policy instruments, plant-specific measures, and targeted support to address key challenges. These measures have worked in synergy to ensure effective emission reduction outcomes.

a) Legal and Regulatory Safeguards

In 2014, the *Regulations of Shanghai Municipality on the Prevention and Control of Air Pollution* came into effect, establishing explicit requirements and penalties for VOC prevention and control and providing a strong legal foundation. For the first time, the regulations mandated that fugitive VOC emissions must be fully captured, requiring that all VOC-emitting production activities must be conducted within enclosed equipment or spaces equipped with gas collection and treatment systems that are kept in continuous operation. The regulations also included specific provisions on the use of VOC-containing products, such as encouraging the use of low-VOC raw materials and products; prohibiting the use of high-VOC content products in environmentally sensitive areas, such as hospitals, schools, and childcare institutions; and promoting the phased adoption of low-VOC products in key sectors, such as petrochemicals, surface coating, and packaging and printing.

b) Standards and Technical Specifications

Over the past decade, Shanghai has developed a comprehensive

set of standards to guide industrial VOC control. A total of 11 emission standards and more than 10 technical specifications for controlling VOCs in key industries—such as automobile manufacturing, furniture manufacturing, and shipbuilding—have been issued. Together, a well-developed management framework for stationary VOC emissions has been established, providing a strong scientific basis. Several of these standards have core indicators that are aligned with, or exceed, best international practices (see Table 3-1).

c) Integrated Policy Mix

A defining feature of Shanghai's VOC control is the coordinated use of multiple policy instruments to generate synergistic effects. During VOC Control 1.0, the government first issued a municipal plan specifying control objectives and tasks. This was followed by the introduction of specific financial support to encourage early action by enterprises through subsidies. At the same time, a VOC pollution discharge fee was implemented by sector and in stages, compelling enterprises to substantially reduce emissions. These policy instruments were closely aligned and mutually reinforced, ensuring the effective delivery of VOC emission reduction outcomes.

d) Plant-Specific Measures

Shanghai was the first city in China to introduce and implement plant-specific measures for VOC control. As early as 2014, the SMBEE required enterprises to develop dedicated plant-specific control plans to guide VOC reduction actions. Since then, this

approach has become the primary instrument and core driver of both the VOC Control 1.0 and 2.0 phases in Shanghai. In 2019, the approach of plant-specific measures was incorporated as a national requirement. To date, more than 100 cities have developed and implemented plant-specific measures for VOC control as part of their emission reduction efforts.

e) Targeted Support

The SMBEE worked jointly with industry associations and relevant sectoral authorities—such as those for printing,

furniture manufacturing, and shipbuilding—to organize more than 20 industry-specific training sessions, which focused on addressing enterprise concerns, clarifying technical requirements, and sharing best practices and advanced control technologies. In parallel, new media platforms were actively used to disseminate emission reduction policies and promote innovative technologies. Through systematic policy guidance and technical assistance, enterprises significantly improved their understanding and capabilities in VOC control, fostering a shift toward proactive control and standardized management.

Table 3-1 Selected Standards and Technical Specifications Issued by Shanghai for VOC Control

No.	Standards and Technical Specifications	Standard Code
1	Emission standards of air pollutants for automobile manufacturing industry (Coating)	DB31/859—2014
2	Integrated emission standard of air pollutants	DB31/933—2015 (Revised in 2025)
3	Emission standard of air pollutants for shipbuilding industry	DB31/934—2015
4	Emission standard of air pollutants for paint, ink and allied products industry	DB31/881—2015 (Revised in 2024)
5	Emission standard of air pollutants for printing industry	DB31/872—2015 (Revised in 2024)
6	Emission standards for odor pollutants	DB31/1025—2016
7	Emission standards of air pollutants from furniture industry	DB31/1059—2017
8	Emission standards of air pollutants for vehicle maintenance and repair industry	DB31/1288—2021
9	Emission standard of air pollutants for pharmaceutical industry	DB31/310005—2021
10	Technical Specifications for the Control of Equipment Leaks of Volatile Organic Compounds	DB31/T 310007—2021
11	The discharge standards of pollutants for semiconductor industry	DB31/374—2024

5. Outcomes

Shanghai has not only achieved significant environmental benefits through VOC control but also stimulated the development of the environmental protection industry, generating mutual gains for both the environment and the economy.

On the environmental side, the continuous implementation of control measures has led to sustained reductions in total VOC emissions, playing a critical role in the coordinated control of $\text{PM}_{2.5}$ and O_3 . The year 2020 marked a major milestone: For the first time, all municipal air quality targets were met, with the AQI attainment rate reaching 87.2%. The annual average $\text{PM}_{2.5}$ concentration declined to $32 \mu\text{g}/\text{m}^3$ —below the Class II concentration limit of $35 \mu\text{g}/\text{m}^3$ for the first time—and continued to fall in subsequent years, reaching $25 \mu\text{g}/\text{m}^3$ in 2022 and remaining consistently below the national standard (Figure 3-2). At the same time, the rapid increase

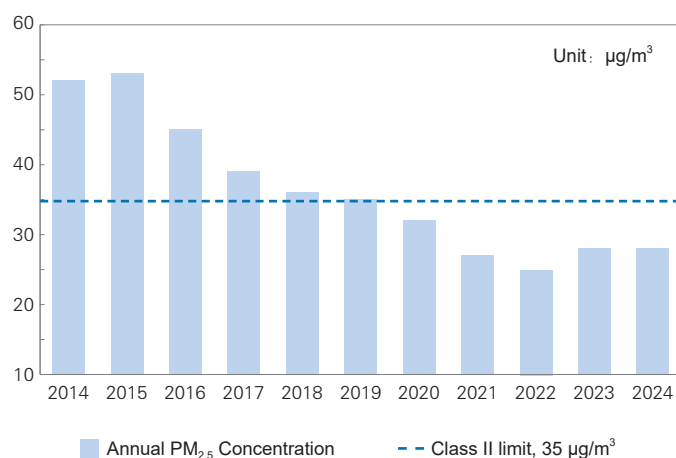


Figure 3-2 Trends in Annual Average $\text{PM}_{2.5}$ Concentrations in Shanghai, 2014–2024

in O_3 pollution was effectively curbed, reversing the peak level recorded in 2017 ($181 \mu\text{g}/\text{m}^3$), with concentrations falling to $145 \mu\text{g}/\text{m}^3$ in 2021 (Figure 3-3).

On the economic side, differentiated subsidy policies effectively spurred enterprise investment and fueled the growth of Shanghai's environmental industry. Driven by both incentives and regulation from the VOC Control 1.0 to 2.0 phases, the demand for VOC control fostered a complete industrial value chain—spanning equipment manufacturing, engineering services, operation and maintenance, and technical consulting—creating new sources of economic growth while promoting technological innovation and enhancing the overall technical capacity and market competitiveness of Shanghai's environmental protection industry.

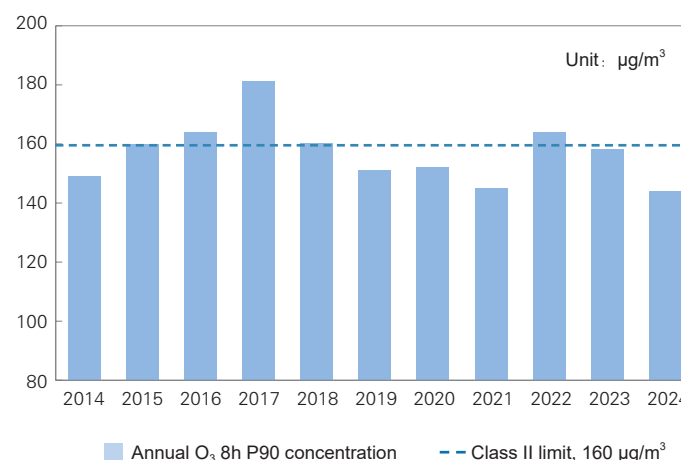


Figure 3-3 Trends in the Annual 90th Percentile of the Daily Maximum 8-hour O_3 Concentration in Shanghai, 2014–2024

6. Key Lessons

Shanghai has developed a replicable and scalable model for controlling VOC emissions from industrial sources, offering valuable insights for other regions. The key lessons can be summarized in four areas.

First is combining top-level design with phased implementation.

Shanghai's VOC control work followed a progressive, step-by-step approach—from establishing the emissions inventory in 2007, to launching pilot projects in 2011, to a phased citywide rollout from 2014 onward, and then advancing into a deepening stage in 2020. This “pilot-first, gradual expansion” approach ensured a smooth transition from targeted control in key enterprises to full coverage across all relevant sectors, delivering steady and effective progress at each stage.

Second is advancing institutional innovation and upgrading the control model. Shanghai took the national lead in 2014 by introducing plant-specific measures to promote enterprises to develop targeted emission reduction plans. As control efforts moved into a deeper phase, this approach was systematically upgraded to a sector-specific model. Under this model, sector-specific measures based on dedicated action lists were developed to regulate VOC emissions in a standardized, list-based manner. This shift went from individualized plans to standardized management, significantly improving precision, scalability, and efficiency in control efforts.

Third is integrating policy coordination with multi-stakeholder engagement.

Shanghai effectively combined positive incentives—such as subsidies—with regulatory constraints, including pollution discharge fees and strict enforcement measures. These policy instruments were designed to reinforce one another, creating a coherent and mutually supportive system. This integrated approach mobilized enterprise initiative, formed strong momentum for VOC reduction, and ensured the effective implementation of control tasks.

Fourth is adopting targeted measures while strengthening law-based governance.

Differentiated standards and technical specifications were developed based on the emission characteristics of different industries, providing clear guidance for enterprises while prioritizing sectors with high emissions, high reactivity, and significant environmental impacts. This enabled a classified and tiered management approach that ensured resources were directed to where they were most needed. At the same time, Shanghai combined strict enforcement with supportive services, offering policy interpretation and technical assistance to enterprises while maintaining regulatory rigor, driving the transition from “external compliance” to “internal motivation” among enterprises.

7. Outlook

As Shanghai enters a new stage of VOC control, it faces higher demands on the completeness of the policy framework, the advancement of technologies, and the refinement of routine management. Going forward, Shanghai will continue to advance full-chain control, integrating source prevention, process reduction, and end-of-pipe treatment.

a) Sustaining Source Reduction

Shanghai will focus on key solvent-use industries, such as coating and ink manufacturing, automobile manufacturing, shipbuilding, construction machinery, furniture manufacturing, and packaging and printing. Efforts will be made to (i) promote the large-scale adoption of low- or zero-VOC raw and auxiliary materials; (ii) encourage enterprises to adopt new technologies and equipment that eliminate or reduce the use of VOCs; and (iii) strictly enforce national and local VOC content standards for products, such as coatings, inks, adhesives, and cleaning agents, while strengthening full-process supervision across production, distribution, and use.

b) Strengthening Process Control

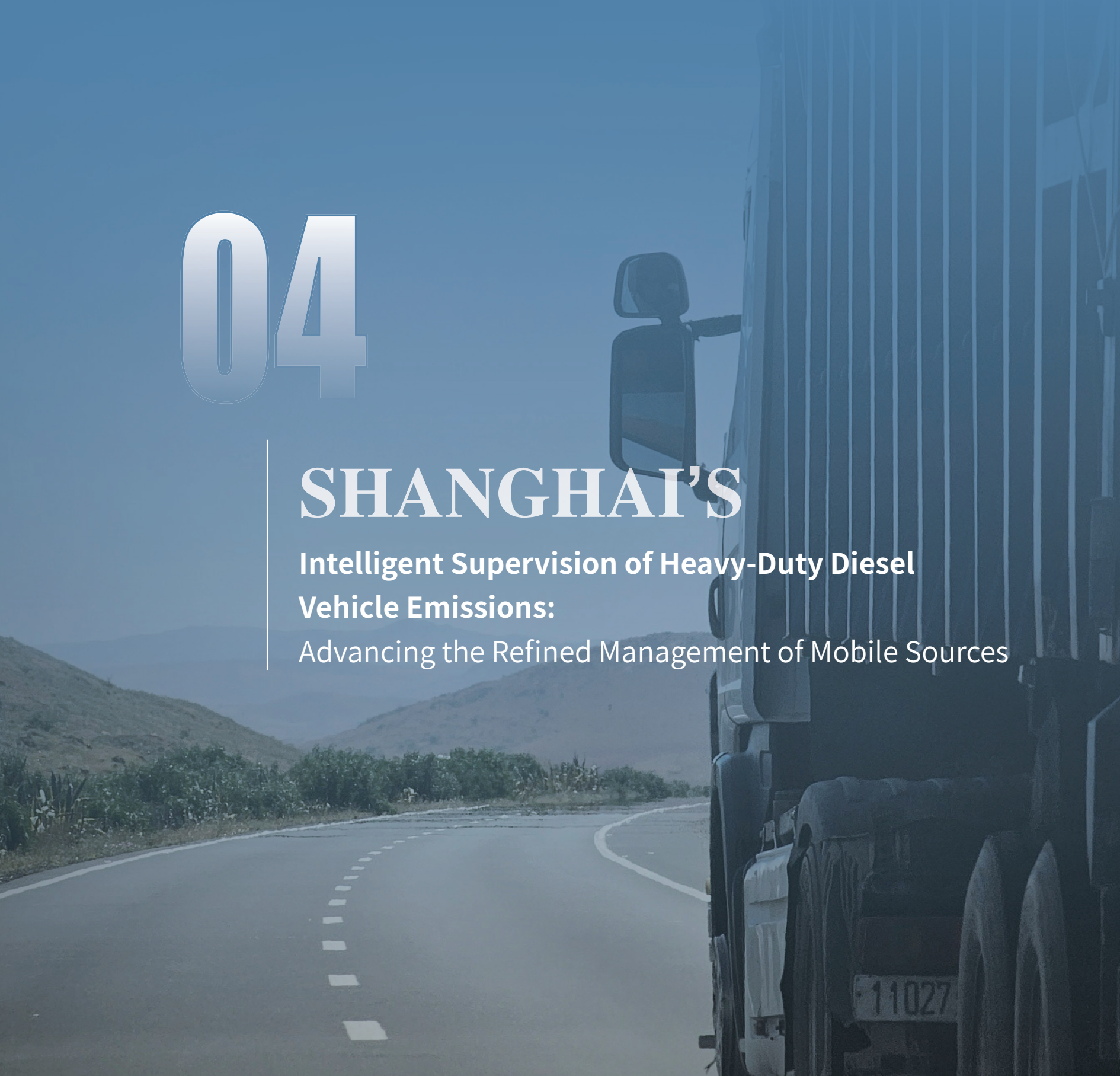
Fugitive VOC emissions remain a key challenge. Future efforts will focus on operating conditions—including plant startup and

shutdown, equipment maintenance, and flare emissions—in sectors such as petrochemicals and chemicals by developing targeted standards and technical specifications and incorporating them into regularized management. For outdoor painting operations in industries such as shipbuilding and repair, Shanghai will further strengthen process control, developing technical pathways to improve exhaust collection efficiency and minimize fugitive emissions.

c) Enhancing End-of-Pipe Treatment

To ensure stable emission reduction performance, Shanghai will implement a more refined and differentiated supervision of end-of-pipe VOC control facilities. For facilities using high-efficiency treatment technologies, such as regenerative thermal oxidizers and thermal oxidizers, the installation of continuous emission monitoring systems will be promoted to achieve real-time monitoring. For facilities using simpler technologies such as activated carbon absorption, Shanghai will prioritize the use of production-condition monitoring technologies based on key parameters, such as temperature, humidity, pressure, and flow. This approach enables low-cost, digital, and routine supervision to ensure the stable and effective operation of VOC control facilities.



The background of the slide is a photograph of a white heavy-duty truck driving on a two-lane asphalt road that curves into the distance. The road has a dashed white line on the left and a solid white line on the right. The landscape is hilly with sparse vegetation. In the background, there are blue-toned mountains under a clear sky. The entire image is overlaid with a semi-transparent blue filter. The truck's side mirror and part of its body are visible on the right side of the frame.

04

SHANGHAI'S

**Intelligent Supervision of Heavy-Duty Diesel
Vehicle Emissions:**

Advancing the Refined Management of Mobile Sources

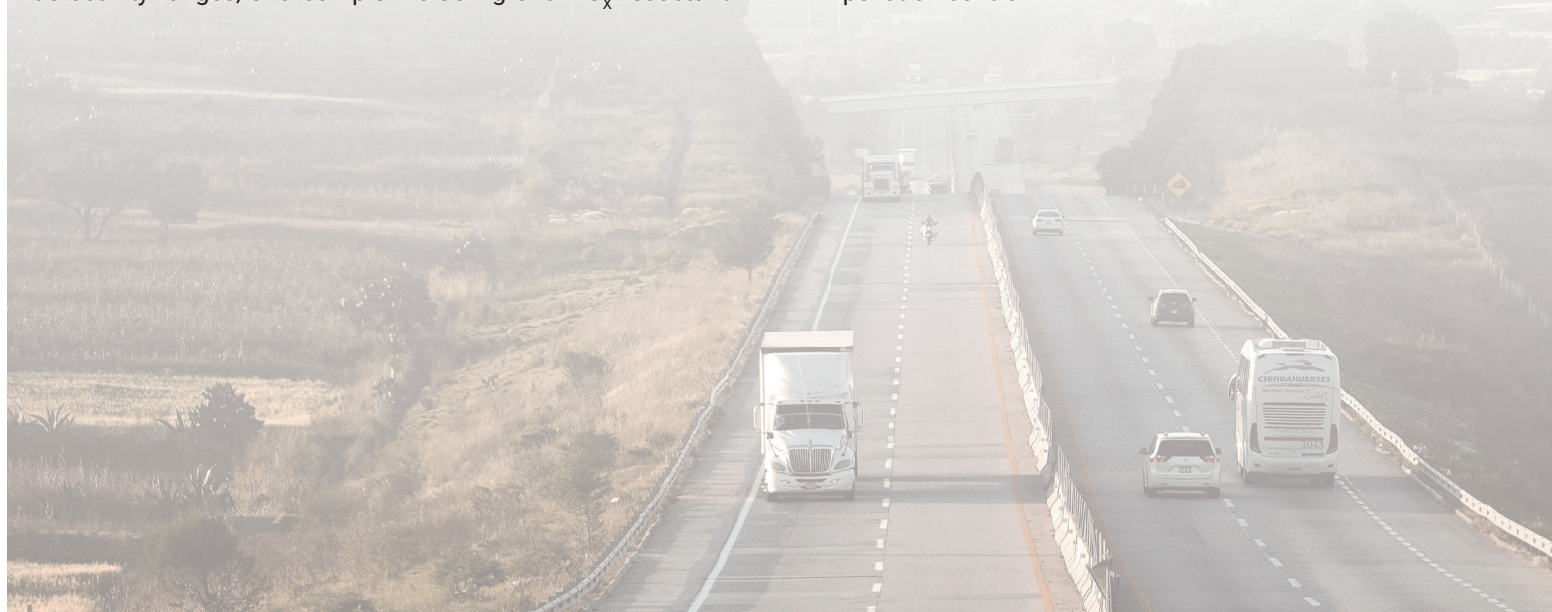
1. Background

As China's international center for economy, finance, trade, shipping, and technological innovation, Shanghai has a vast demand for road freight dominated by heavy-duty diesel vehicles (HDDVs). By the end of 2024, HDDVs accounted for only 5% of Shanghai's vehicle fleet but contributed 83% of NO_x and 81% of primary $\text{PM}_{2.5}$ emissions from motor vehicles.

HDDVs operate at high loads throughout the year and experience significant degradation in exhaust after-treatment systems and inconsistent fuel quality. Consequently, their emissions remain high; monitoring data show that over 5% of HDDVs exhibit excessive emissions, fault alarms, or abnormal urea consumption, with emission levels three to five times higher than normal. In addition, the centralized and real-time regulation of HDDVs remains extremely challenging due to a large number of operators, wide activity ranges, and complex refueling and NO_x reductant

supply networks. Big data analysis indicates that more than 280,000 HDDV trips occur in and out of Shanghai each day, with around 5% of them traveling over 300 km per day and a total of 1,158 diesel and NO_x reductant refueling points in operation—including 379 non-public stations—all of which pose substantial challenges for regulatory supervision.

To address these issues, Shanghai has shifted from a traditional approach centered on upgrading new vehicle standards and phasing out old vehicles to a smart, full-chain management model integrating vehicles, fuels, roads, and enterprises. Led by the Shanghai Academy of Environmental Sciences, an Intelligent Emissions Supervision System for HDDVs (hereinafter refer to as "System") was developed, enabling intelligent, automated regulation and thus promoting precise, scientific, and law-based pollution control.



2. Evolution

a) Stage I (2018–2021)

In 2018, Shanghai took the lead in deploying remote sensing equipment for on-road vehicle emission monitoring along key roads. This strengthened on-road inspection and enforcement while enabling data interconnection among national, provincial, and municipal emission monitoring platforms, laying the groundwork for a citywide remote monitoring network.

In April 2020, several municipal departments in Shanghai jointly issued a work plan to advance the remote supervision of HDDV

emissions. The plan called for accelerating the installation of on-board diagnostic (OBD) terminals and the construction of a supervision system, aiming to achieve the near-full coverage of OBD installation for key vehicles by the end of 2020. By the end of 2021, the system architecture had been largely completed, equipped with core capabilities such as concurrent big-data ingestion and the dynamic analysis of emission characteristics.

b) Stage II (2022–2024)

Shanghai has established China's first large-scale Intelligent

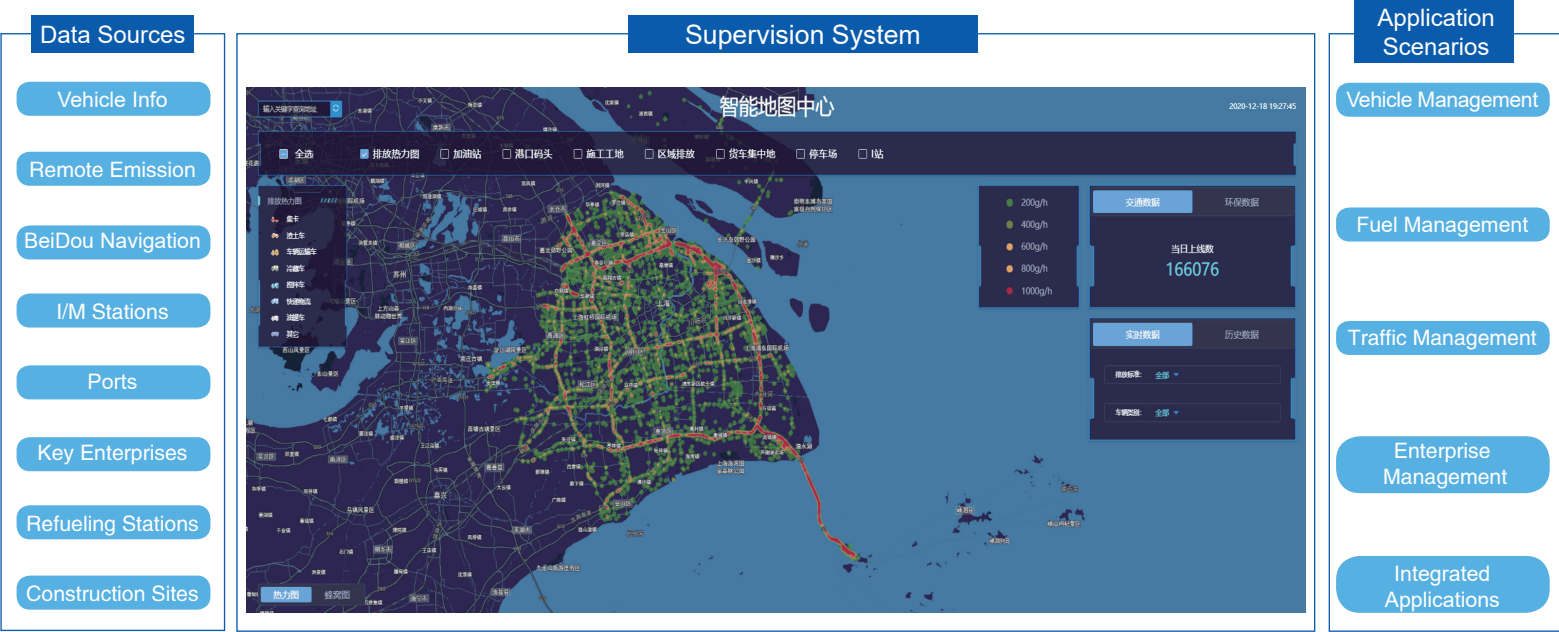


Figure 4-1 Schematic Diagram of the Big Data-Based Supervision System

Note: I/M stations refer to vehicle emission inspection stations (I stations) and vehicle maintenance stations (M stations).

Emissions Supervision System for HDDVs (Figure 4-1). By October 2025, more than 200,000 HDDVs had been connected to the system, enabling the real-time transmission of emission data. Many supervision scenarios and functions have been progressively developed, covering the entire chain of vehicles, fuels, roads, and enterprises, as well as multi-level management across individual vehicles, fleets, and industries. The System delivers a comprehensive citywide profile of vehicle operations and emissions through geofence-enabled real-time monitoring and model-based statistical analytics. It achieves second-level temporal granularity and meter-level spatial precision, enabling the generation of high-resolution emission maps for HDDVs across different regulatory zones.

Built on this system, Shanghai has realized the integrated management of vehicles, fuels, roads, and enterprises:

- Vehicle management: Algorithms for emission feature extraction were developed to create multidimensional vehicle

emission profiles and establish a graded vehicle emission management system.

- Fuel management: Algorithms were designed for the identification, supervision guidance, and dynamic tracking of non-public refueling stations, forming a closed-loop management process encompassing identification, classification, on-site inspection, and evidence transfer.
- Road management: The system enables the identification and regulation of high-emission road segments, accurately capturing the key transport corridors contributing most to HDDV emissions in critical hub areas.
- Enterprise management: Methods were developed for vehicle supervision and the emission characterization of vehicle-related enterprises, including algorithms for hotspot identification and tracking across industries, as well as emission management frameworks for major vehicle users and sector-specific emission profiling.

3. Framework

a) Multi-Source Integrated System Architecture and Digital Foundation

The system is built on emission monitoring data, integrated with vehicle technical specifications, operational data, and geographic data, forming a system architecture and digital infrastructure tailored to Shanghai’s emission control needs for HDDVs. Following a layered design concept, the system architecture consists of five layers—the network layer, infrastructure layer, digital foundation layer, support layer, and application layer,

simultaneously integrating both a data standardization and management framework and a system security assurance framework (Figure 4-2).

In terms of big data management, the system is developed on the Hadoop ecosystem using distributed architecture and cluster servers. It utilizes HDFS for data storage, Kafka for data transmission, and HBase for random real-time read/write access, ensuring high reliability, high performance, column-oriented storage, and scalability. The MapReduce framework is used for

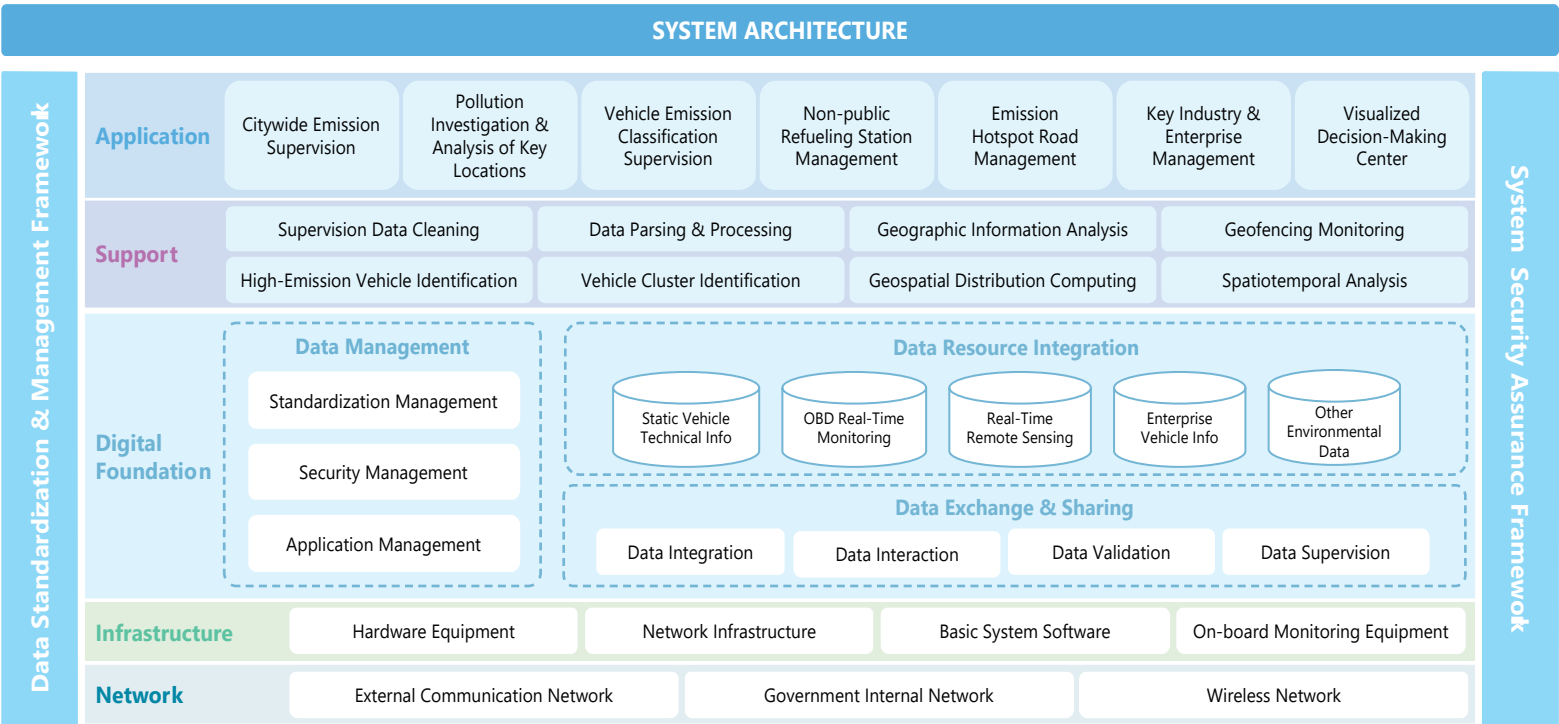


Figure 4-2 Schematic Diagram of the System Architecture

large-scale parallel computing, enhancing both data processing efficiency and security. According to operational needs, data are further mined and analyzed, with the results visualized through business intelligence (BI) dashboards for intuitive display and decision support.

b) Citywide Overview with High Spatiotemporal Resolution

By integrating big data resources, such as real-time BeiDou

navigation data, remote emission supervision data, and geographic point-of-interest data, the citywide overview module of the system provides a comprehensive picture of HDDV operations and emissions across Shanghai and key areas within it, covering different vehicle models, emission standards, and operational areas (Figure 4-3). Using a vector-slicing algorithm, data are transformed into dynamic vector maps that visualize the spatial and temporal distribution of pollutant emissions, energy use, and CO₂ emissions.

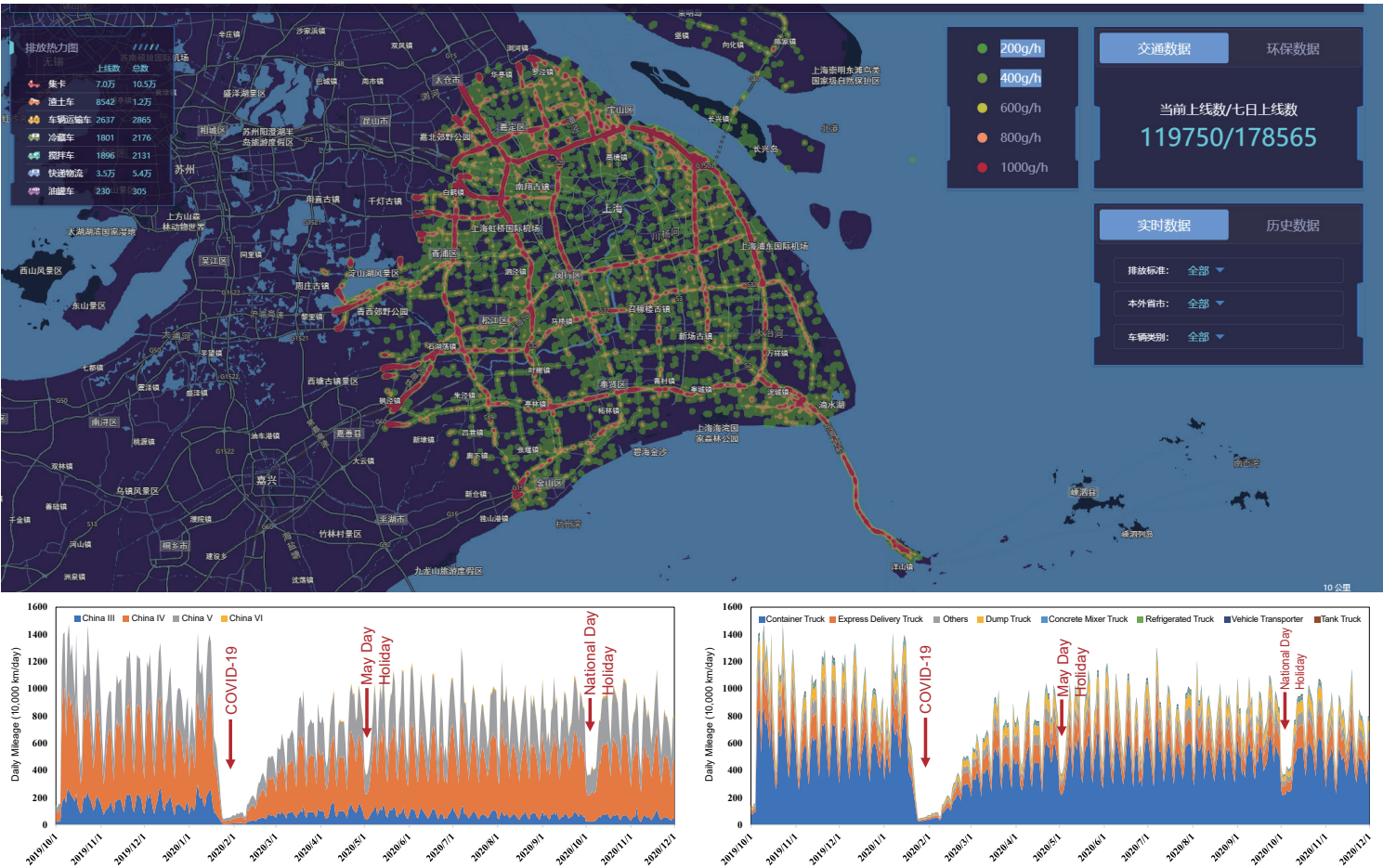


Figure 4-3 Real-Time Emission Variations of HDDVs by Vehicle Model and Emission Standard

c) Big Data–Driven Graded Vehicle Regulation

The system features a closed-loop management module for high-emission and malfunctioning vehicles. Using supervised learning algorithms, it enables the real-time tracking of actual vehicle emissions and diagnosis of emission-related faults, identifying and alerting potential issues such as improper urea use or tampering with exhaust aftertreatment devices. An additional high-emission vehicle interface was developed to facilitate real-time data exchange with the transport authority, allowing the continuous monitoring of fleet operations and dispatching for major vehicle users. Building on these capabilities, the system can automatically generate lists of malfunctioning

vehicles, major vehicle users, and centralized parking sites, while maintaining a blacklist system that is regularly shared with law enforcement and regulatory departments, thus realizing an intelligent identification–location–control supervision chain.

Meanwhile, the system also includes a module for exempting clean HDDVs from periodic emission inspections. By analyzing data completeness, continuity, and any occurrence of excessive emissions or emission-related faults, the system evaluates whether each connected HDDV maintains stable compliance with emission standards, determining its eligibility for inspection exemption (Figure 4-4).

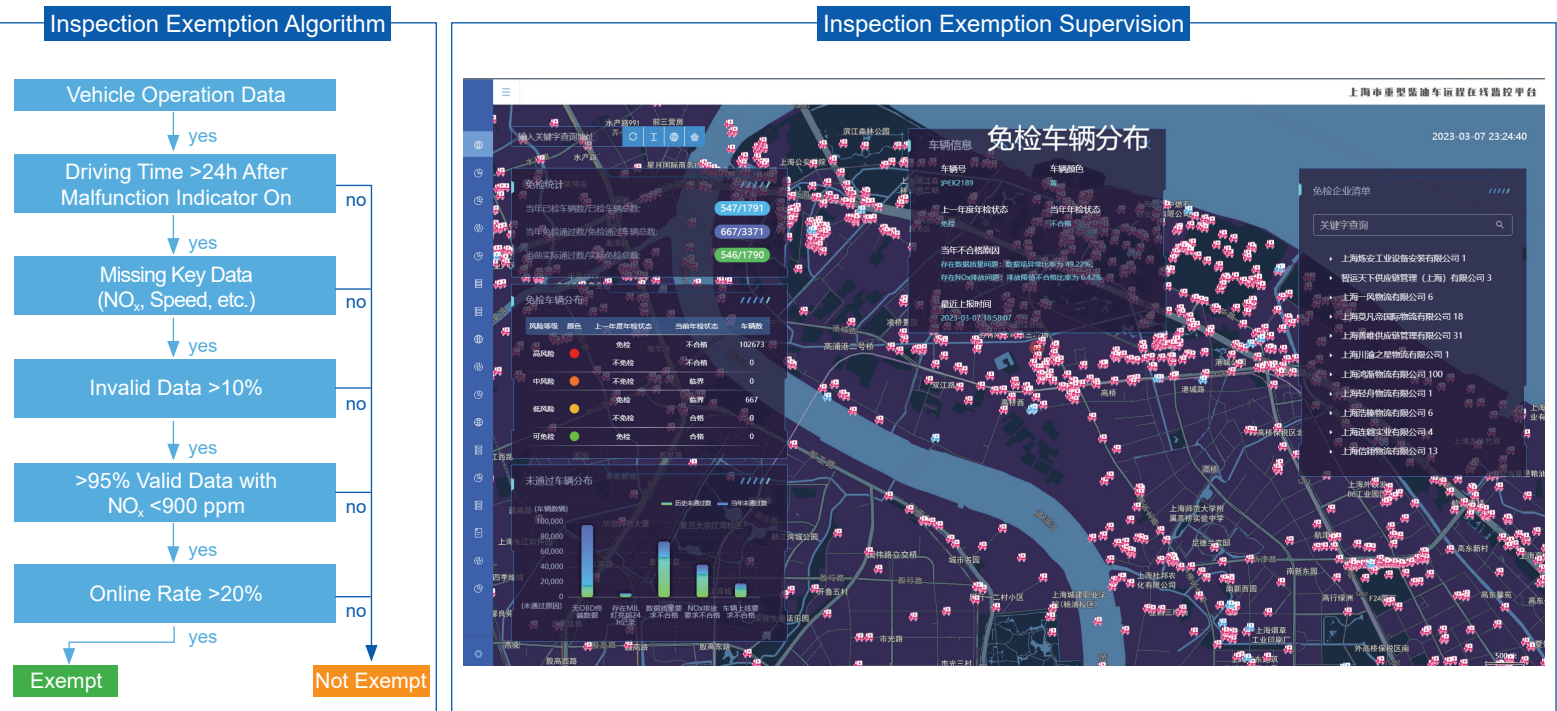


Figure 4-4 Management Framework for Exempting Clean HDDVs from Periodic Emission Inspections

d) Closed-Loop Regulation of Non-Public Refueling Stations

Using the real-time monitoring of vehicle fuel tank levels, the system applies to the Density-Based Spatial Clustering of Applications with Noise (DBSCAN) clustering algorithm together with reverse geocoding techniques to develop a dynamic supervision module for non-public refueling stations. By continuously comparing this information with the geographic data of public refueling stations and logistics hubs, the system enables the real-time monitoring of the locations, refueling frequency, serviced vehicles, and major vehicle users associated with non-public refueling activities.

Based on this application, Shanghai has established a closed-loop regulation mechanism for non-public refueling stations. The system regularly transmits station lists to law enforcement and regulatory authorities, providing key leads for identifying potentially non-compliant refueling sites and significantly improving regulation efficiency. To support on-site enforcement, a refueling station inspection mini-program was also developed for the use of district-level departments.

These tools realize a closed-loop supervision process for non-public refueling stations encompassing identification, classification, on-site inspection, and evidence transfer.

e) Origin–Destination Analysis-Based Road Supervision

Integrating vehicle operation and emission patterns, the system applies origin–destination and road-network matching algorithms to identify and monitor road segments with concentrated emissions, providing decision support for regional mobile source

emission reduction. It features an emission-tracking module for freight corridors serving key enterprises and port terminals, enabling the real-time monitoring of vehicle arrivals and departures, travel trajectories, and emission levels. This allows the system to pinpoint major transport corridors responsible for HDDV emissions in critical logistics hubs and supports optimized vehicle dispatching in key areas.

In addition, the system includes a real-time assessment module for evaluating the implementation and effectiveness of the clean transportation measures adopted by major enterprises and ports, particularly during major events or heavy-pollution response periods. A dedicated hotspot identification–marking–tracking algorithm enables the continuous monitoring of the freight corridor emissions associated with these enterprises and port terminals, ensuring dynamic and precise supervision.

f) Geofencing-Based Vehicle Users Management

By analyzing the arrival and departure patterns of construction waste dump trucks, container trucks, box trucks, and oil tanker trucks, the system can dynamically identify construction sites, storage yards, logistics hubs, and key enterprises. Combined with road, waterway, and railway network data, it automatically generates geofences around these areas, providing the foundation for monitoring vehicle operations and assessing the adoption of clean vehicle use. This greatly improves the efficiency of identifying centralized parking sites and offers precise supervision guidance for regulatory authorities.

Using the automatically identified enterprise geofences together with real-time vehicle operation data, the system monitors the

operational and emission performance of vehicles serving construction sites, storage yards, logistics hubs, and key enterprises. This enables dynamic emission tracking and the characterization of actual production and emission activities at the enterprise level, providing environmental authorities with real-time insights into sectoral activities and the implementation of control measures, while also delivering data-driven support for regional emission assessments.

g) Digital Twin Concept-Based Visualization Center

To better support decision-making by environmental authorities, the system includes a visualization interface for supervising HDDV emissions. Applying the digital twin concept, it integrates various functional modules, layers, and data elements onto a single interactive map using geospatial visualization technology, creating a smart-mapping center. In parallel, BI visualization tools are used to aggregate real-time outputs from different functional modules, hierarchically integrate diagnostic data, and develop an environmental data visualization center.



4. Outcomes

The system has effectively supported the implementation of major emission reduction measures, including phasing out old vehicles, traffic restrictions, and inspection exemptions for clean vehicles.

The system has become an important tool for evaluating the effectiveness of HDDV pollution control measures, particularly for tracking and assessing the impact of phasing out old diesel vehicles. During the phase-out of China III diesel trucks, the system was used to analyze changes in the operation and spatial distribution of China III, China IV, and China V HDDVs across the city from the end of 2019

to the end of 2020 (Figure 4-5). The analysis showed that, following the phased restriction and phase-out of China III diesel vehicles, $PM_{2.5}$ and NO_x emissions decreased by 13.1% and 13.4%, respectively, compared with pre-implementation levels.

In addition, the system has played a vital role in implementing the inspection exemption policy for clean diesel vehicles. To enhance in-use vehicle regulation efficiency, boost confidence in the road transport sector, and reduce compliance costs, a policy was introduced allowing eligible HDDVs to be exempted from periodic emission inspections based on remote online emission supervision

data. The inspection exemption identification module was officially launched on January 1, 2023. As of the end of September 2025, approximately 92,000 diesel vehicles had completed exemptions, saving vehicle owners more than CNY 14.72 million in inspection costs. Beyond reducing the financial burden on vehicle owners, the policy also encourages more proper vehicle operation, the proper use of diesel and urea, and the timely repair of engine and aftertreatment system faults, thereby lowering emissions and improving the overall compliance rate of in-use diesel vehicles.

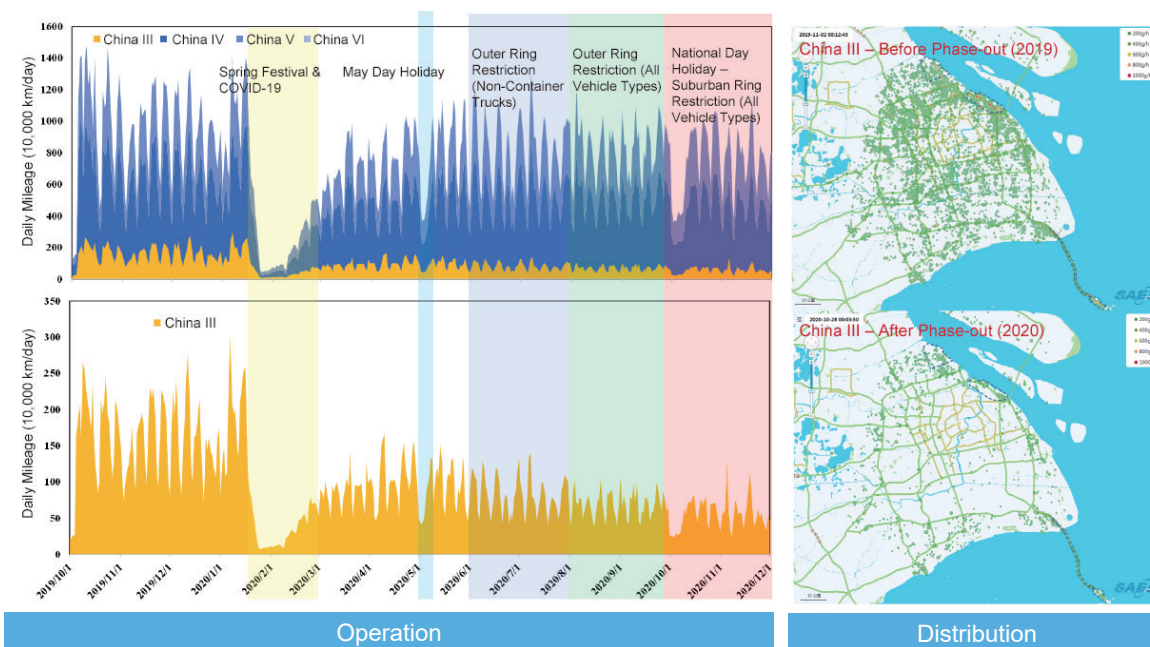


Figure 4-5 Effects of Traffic Restrictions and Phase-Out Measures on China III Diesel Vehicles

5. Innovations

The system demonstrates three major innovations:

The real-time, all-day supervision of HDDV operation and emissions in a megacity. By integrating real-time BeiDou positioning, remote emission supervision, and geographic point-of-interest data, the system establishes an advanced architecture capable of high-speed, concurrent data reception, analysis, and storage. It enables the real-time monitoring of HDDV operations and the emission of various types of diesel vehicles across the entire city and in key areas. The system can identify freight corridors linked to key enterprises and port terminals and is capable of dynamic emission tracking, effectively eliminating blind spots in citywide HDDV regulation and guiding mobile source regulators to focus on high-impact targets.

Intelligent full-chain supervision across vehicles, enterprises, industries, and regions. By combining vehicle emission and fault data with operational and activity information, the system applies

high-emission vehicle recognition algorithms, AI-based clustering algorithms, and reverse geocoding techniques to realize the bottom-up integrated supervision of vehicles, affiliated enterprises, industries, and major vehicle users. This approach addresses long-standing challenges, such as low efficiency in identifying high-emission vehicles during periodic inspections, as well as limited precision and deterrence in roadside checks.

Closed-loop management covering the full chain of vehicles, fuels, roads, and enterprises. The system integrates modules for high-emission vehicle identification, non-public refueling station recognition, freight corridor detection and tracking, and major vehicle user supervision, eliminating blind spots in in-use compliance, fuel management, freight corridor monitoring and optimization, and key vehicle user oversight. It also bridges supervision needs across multiple levels, enhancing coordination and significantly improving the overall effectiveness and precision of HDDV emission supervision.

6. Outlook

Building on the current system, Shanghai will further expand its supervision capabilities by developing new functional modules and application scenarios, including multi-source data integration, regional dynamic operation and emission monitoring, emission health diagnostics, the standardized management and traceability of refueling sites and substandard fuels, traffic flow and emission

forecasting for key roads and sites, VOCs leakage monitoring for vehicles transporting volatile chemicals, operation and dust control supervision for construction waste dump trucks in dust-prone industries, and the automated evaluation of temporary control measures and major events.



The background of the slide is a photograph of a city skyline at dusk. In the foreground on the left is a large, curved building with a complex, textured facade, possibly a stadium or arena. Behind it and to the right are several tall, modern skyscrapers with glass facades that reflect the twilight sky. The sky is a deep blue with some light clouds. The overall scene is urban and modern.

05

CHENGDU'S

Pilot of Near-Zero Carbon Construction Sites:

Advancing Synergistic Pollution Mitigation and
Decarbonization in the Construction Sector

1. Background

From 2016 to 2020, Chengdu saw continuous improvement in air quality, with the annual average $\text{PM}_{2.5}$ concentration reaching $41 \mu\text{g}/\text{m}^3$ in 2020—a 28.1% reduction compared to 2015. However, since 2021, the pace of improvement has slowed significantly. Between 2021 and 2022, the annual average $\text{PM}_{2.5}$ concentration remained at around $40 \mu\text{g}/\text{m}^3$, still far from the national Class II standard of $35 \mu\text{g}/\text{m}^3$. At the same time, O_3 pollution has become more prominent. NO_2 , a key precursor for both $\text{PM}_{2.5}$ and O_3 , has maintained levels among the lowest of the 168 key cities in China, becoming a critical factor limiting the effectiveness of coordinated pollution control.

Mobile sources and fugitive dust are major contributors to air pollution in Chengdu. By the end of 2022, mobile sources accounted for 87% and 25% of the emissions of NO_x and VOCs, respectively, with a 38.8% contribution to $\text{PM}_{2.5}$. Fugitive dust contributed about 20% to $\text{PM}_{2.5}$, with fluctuations due to the increase in construction sites. The primary PM emissions from construction and road fugitive dust accounted for more than 60% of total PM emissions in the city.

Construction sites are hotspots for the combined emissions of fugitive dust and mobile sources. During construction, numerous construction machinery and transport vehicles operate intensively, directly emitting large quantities of NO_x , VOCs, and PM while generating substantial fugitive dust. Moreover, the high energy consumption of diverse construction equipment leads to significant carbon emissions. In 2022, carbon emissions from the construction

phase of the national construction industry accounted for 26.6% of China's total energy-related carbon emissions.

To address the challenges, Chengdu has made the near-zero carbon construction site pilot project a breakthrough point, actively exploring the promotion of new energy construction machinery and transport vehicles in construction sites and deeply integrating green and low-carbon concepts into the entire construction process, driving the green transformation across the entire life cycle from construction to operation. The first pilot project is located south of the Eastern Section of Tianfu New Area Science City Road, within the Tianfu New Area Tianfu Yongxing Laboratory, covering an area of approximately 65 acres with a total building area of approximately $154,143 \text{ m}^2$, as shown in Figure 5-1.



Figure 5-1 Rendering of the Pilot Project

2. Evolution

The Chengdu Municipal Bureau of Ecology and Environment (CMBEE) has actively taken the lead, organizing multiple specialized meetings to discuss the pilot project’s objectives, technical implementation challenges, and the various barriers encountered. These meetings focused on identifying practical, actionable solutions to ensure the smooth progress of the pilot project. In October 2023, the first specialized workshop was held,

where the overall approach of government leadership and enterprise implementation was clarified. This was followed by several working meetings to further refine the implementation plan. By April 2024, the first pilot project was officially approved, marking the commencement of the near-zero carbon construction site pilot implementation phase, as shown in Table 5-1.

Table 5-1 Key Milestones in the Advancement of Chengdu's Near-Zero Carbon Construction Site Pilot Project

Date	Department	Meeting Content
31 October 2023	CMBEE	Organized the first seminar, inviting enterprises and experts to discuss the implementation path. The pilot project principles were initially clarified, emphasizing government leadership and enterprise implementation. The project adopted a trial-and-evaluation approach, focusing on the adoption of new energy non-road mobile machinery and trucks and integrating green and low-carbon concepts throughout the construction process.
November 2023– February 2024	CMBEE CMHURDB	Organized the research and development of the pilot project plan, inviting machinery manufacturers to discuss the adoption of new energy machinery and collaboration on pilot projects, as well as joint study machinery replacement and cost accounting.
6 March 2024	CMBEE CMHURDB	Jointly issued the <i>Chengdu Near-Zero Carbon Construction Site Pilot Project Plan (Trial)</i> and organized districts, counties, and construction units to actively apply for the pilot construction sites.
25 April 2024	CMBEE CMHURDB	Conducted site visits to the applied pilot construction sites and approved the first near-zero carbon construction site pilot project—the Tianfu Yongxing Laboratory Park Construction Project (Phase I).

Note: CMHURDB refers to the Chengdu Municipal Housing and Urban–Rural Development Bureau.

3. Framework

Chengdu has established a multi-departmental coordination mechanism in which all parties assume clearly defined roles and jointly build a management system that spans the entire construction process through government–enterprise collaboration.

Government authorities are responsible for policy formulation, overall coordination, and progress tracking:

- The CMBEE takes the lead in developing the pilot plan and implementation pathways, organizes discussion meetings to resolve issues such as new energy equipment matching and cost accounting, approves pilot projects, and monitors monthly progress.
- The Chengdu Municipal Housing and Urban–Rural Development Bureau (CMHURDB) co-issues the pilot plan, participates in site selection and management, supervises the implementation of low-carbon construction measures, coordinates between developers and construction contractors, and promotes the application of new energy machinery.
- District-level authorities formulate localized pilot policies, establish dedicated task forces to strengthen organizational support, ensure the availability of charging facilities, coordinate the supply of new energy concrete mixer trucks, manage the nearby disposal of construction waste, and optimize nighttime construction schedules to ensure the timely advancement of the pilot project.

Enterprises fulfill their construction responsibilities:

- The developer commissions a third-party agency to conduct carbon accounting, supports the implementation of emission reduction measures, and ensures data accuracy and the achievement of reduction targets.
- The construction contractor incorporates near-zero carbon requirements into their plans, designates responsible staff, implements the replacement of new energy equipment and energy-saving measures, and cooperates in data monitoring and emission reduction optimization.
- The third-party agency independently performs monitoring and evaluation, develops carbon accounting methodologies, and establishes a real-time data tracking system, ensuring data accuracy and providing timely recommendations for emission reduction.
- Equipment suppliers provide new energy equipment and participate in matching and cost-accounting to support the transition to cleaner construction machinery.

4. Supporting Measures

In advancing the near-zero carbon construction site pilot, the focus is on new energy replacement, supported by whole-process management and complemented by measures such as photovoltaic power generation and pollution control, creating a comprehensive support system.

a) New Energy Replacement and Supporting Measures

The pilot project focuses on the replacement of two major categories of equipment—construction machinery and heavy-duty trucks. Led by the CMBEE, the project engages multiple new energy equipment manufacturers to carry out studies, driving the large-scale promotion of new energy on-site equipment. A series of support measures have been introduced, including establishing dedicated charging channels for new energy heavy-duty trucks, coordinating temporary sites to install charging facilities and coordinating grid capacity to meet the pilot projects’ electricity demand, facilitating the targeted supply of new energy concrete mixer trucks, and enhancing the management of nighttime concrete pouring and the nearby disposal of construction waste. For construction processes where new energy equipment is not yet technically feasible, management-based emission reduction measures are adopted, such as optimizing vehicle routes and adjusting operation schedules.

The new energy replacement of equipment has already achieved notable phased progress (Table 5-2). During the earthwork excavation stage, limited market supply, long transport distances, tight construction schedules, and complex geological conditions have restricted the replacement; only 26% of construction waste dump truck trips were replaced by new energy vehicles, and only one

Table 5-2 Status of New Energy Equipment Replacement

Equipment Type	New Energy Replacement Status
Construction waste dump trucks	26% of total trips
Concrete mixer trucks	93.5% of total trips
Water trucks	44% of total operations
Anchor drilling rigs	100% replacement
Boom lifts	100% replacement
Excavators	One new energy excavator used for backfilling
Concrete pumps	36% of total workload
Scissor lifts	100% electrification
Raw material transport trucks	Steel transport, partly carried out by new energy trucks

new energy excavator was used for backfilling. In contrast, during the foundation and main structure construction stage, replacement advanced significantly; new energy concrete mixer trucks accounted for 93.5% of total trips; anchor drilling rigs, boom lifts, and scissor lifts achieved 100% electrification; while new energy water trucks completed 44% of total operations, and new energy concrete pumps accounted for 36% of the total workload.

b) Fugitive Dust Control and Green Construction

To effectively control fugitive dust, the pilot project introduced an innovative tower crane-mounted mist-spraying system. A total of six tower cranes were used during construction, all equipped with mist cannons. During the main structure phase, belt-type spraying systems were installed every four floors to ensure full-coverage fugitive dust control throughout vertical construction. Additionally, seven 360-degree high-pressure rotary sprayers were deployed to cover all major roads and excavation pits, providing comprehensive on-site dust suppression.

Beyond fugitive dust control, the pilot project also emphasizes green construction practices. The site is equipped with 48 m² of photovoltaic panels and 14 m² of cadmium telluride power-generating glass, generating a total of 5,267 kWh, which meets about 6% of the office area’s electricity demand. Renewable energy facilities, including seven solar streetlights and six light-emitting diode (LED) energy-saving lamps, have been installed to illuminate roads and excavation areas. In addition, construction waste, including concrete and bricks, is collected and processed on-site through crushing, washing, and grading. The material is then remolded using a stone-forming machine into low-carbon recycled building materials, which are reused for site paving, thereby reducing embodied carbon emissions from construction activities.

c) Whole-Process Management

This pilot project has established a monitoring–verification–optimization closed-loop system and developed an intelligent carbon monitoring platform (Figure 5-2). The monitoring system enables the real-time display of emission data and the dynamic adjustment of emission reduction measures while maintaining both paper-based and electronic ledgers under a standardized management process. A specialized technical team conducts energy consumption monitoring for major emission sources—including construction machinery, transport vehicles, and key energy-consuming equipment—and verifies related records, such as refueling, charging, electricity meter readings, and on-site power generation, ensuring data accuracy and reliability to provide a robust basis for science-based decision-making.



Figure 5-2 Carbon Monitoring System for Near-Zero Carbon Construction Sites

5. Outcomes

The Pilot Project is China’s first life cycle green and low-carbon project, covering design, construction, and operation and delivering significant environmental and social benefits.

On the environmental side, the project greatly reduced the multiple environmental pressures associated with construction. As shown in Table 5-3, the project achieved remarkable emission reductions of 37% for SO₂, 22% for NO_x, 17% for VOCs, 19% for PM₁₀, and 19% for PM_{2.5}. The foundation and main structure stages showed notably higher replacement rates than the earthwork stage, with corresponding pollutant reductions of around 50% and SO₂ reduction reaching 76%. The integration of photovoltaic systems, solar streetlights, and LED lighting further reduced dependence on the traditional power grid and fossil energy, while the use of energy-efficient and recycled materials cut energy consumption and promoted resource reuse. Overall, the project achieved a cumulative energy saving of 1.55 million

kWh, 52% lower energy consumption than conventional buildings, establishing a benchmark for ultra-low-energy green construction.

On the social side, the project demonstrates how green and low-carbon principles can guide the entire construction process and generate broad social value. First, it promotes industry-wide green transformation, shifting the construction sector from a high-carbon model toward a low-carbon model, providing a replicable and scalable experience. Second, it improves local living conditions by reducing noise, fugitive dust, and exhaust pollution, minimizing impacts on nearby communities and enhancing residents’ environmental awareness. Third, it creates new employment and drives skills upgrading, as demand for new energy equipment maintenance and monitoring systems generates new jobs and fosters workforce transition toward green and digital skills. Finally, it enhances Chengdu’s image as a sustainable city, strengthening its resilience and leadership in the field of green and low-carbon construction.

Table 5-3 Reductions in Air Pollutants and CO₂ Emissions

Stage	Category	SO ₂ (kg)	NO _x (kg)	VOCs (kg)	PM ₁₀ (kg)	PM _{2.5} (kg)	CO ₂ (t)
Earthwork	Estimated	74.9	3117.6	297.4	159.6	158.9	1174.8
	Actual	52.3	2770.6	283.6	150.7	150.2	913.1
	Reduction	22.6	347.0	13.8	9.0	8.7	261.7
	Reduction Rate	30%	11%	5%	6%	6%	22%
Foundation & Main Structure	Estimated	12.1	1238.2	113.7	73.6	72.9	469.0
	Actual	2.9	625.1	56.8	37.6	37.1	196.4
	Reduction	9.2	613.1	56.9	36.0	35.9	272.5
	Reduction Rate	76%	50%	50%	49%	49%	58%
Since Pilot Project Launch	Estimated	87.1	4355.7	411.1	233.2	231.9	1643.8
	Actual	55.2	3395.7	340.4	188.3	187.2	1109.5
	Reduction	31.9	960.1	70.7	44.9	44.6	534.3
	Reduction Rate	37%	22%	17%	19%	19%	33%

6. Outlook

The near-zero carbon construction site pilot in Chengdu still faces multiple challenges and requires targeted, refined measures in the following five areas.

a) Advancing New Energy Equipment Supply

The limited market supply and made-to-order production of new energy construction machinery, with few leasing options, further constrain its use. Going forward, Chengdu will introduce fiscal subsidies and incentives, encouraging manufacturers to expand production and supply. The city will also promote the application of mature technologies, such as hydrogen heavy-duty trucks and electric excavators, and develop microgrids and integrated “photovoltaic (PV)+ energy storage” temporary power systems, advancing the near-zero carbon transition from a life cycle perspective.

b) Enhancing Whole-Process Supervision

As post-construction data are non-reproducible, accurate monitoring during the construction phase is essential. If pollution and carbon management is not integrated effectively during implementation, problems such as delayed reporting, irregular data entry, and inaccurate monitoring may occur, compromising data reliability. To address this, Chengdu continues to strengthen the use of intelligent monitoring platforms for whole-process supervision and introduces third-party verification to ensure transparency and traceability, providing robust support for scientific decision-making.

c) Strengthening Risk Dynamic Management

Potential risks, such as equipment shortages, inefficient transport routes, and unstandardized construction organizations, must be identified in advance to minimize the impact on schedule, cost,

and emission reduction outcomes. Through scientific planning, the city is capable of integrating pollution and carbon reduction requirements into the entire project life cycle—from project approval and design to construction, acceptance, and operation—achieving comprehensive emission reduction across construction sites. Dynamic adjustments, such as coordinating equipment supply and optimizing logistics, should also be emphasized to enhance resilience and ensure steady project progress.

d) Coordinating Cost and Schedule Optimization

Large-scale new energy construction machinery is scattered nationwide, and high transport costs often exceed usage costs. In addition, new energy construction waste dump trucks and concrete mixer trucks have limited capacity; without proper route planning, transport inefficiencies may delay schedules and raise costs. Chengdu aims to optimize transport routes, coordinate nearby resources (such as disposal sites and charging facilities), and balance initial investment with long-term energy savings to reduce time and cost pressures and ensure smooth project delivery.

e) Phased Development of Pilot System

The near-zero carbon construction site pilot must cover the entire project cycle—from design and construction to completion—rather than focusing on a single stage. Different project types also require differentiated evaluation standards, posing high technical and management challenges. Currently, the pilot focuses mainly on building construction sites, while other categories have yet to be included. In the next phase, Chengdu will expand the pilot program step by step, summarize practical experience, establish replicable and scalable implementation and evaluation frameworks, and gradually extend the model to other project types.

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