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A Study of Smog Issues and $PM_{2.5}$ Pollutant Control Strategies in China

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ABSTRACT

The increased occurrence of smoggy days in major Chinese cities is of major concern to the general public. This paper explores the major sources of $PM_{2.5}$ pollutants, a key contributor to the smog in Beijing, one of China's largest cities. Evidence indicates that the secondary $PM_{2.5}$ particles formed through NO_x, SO_x, NH_3, VOCs, etc. have a strong impact on human health. As a result, $PM_{2.5}$ pollution control should not simply focus on controlling particulate emission, but should involve adopting an integrated multi-pollutant control strategy. In addition to identifying the major sources of $PM_{2.5}$, this paper explores its impact on environmental and human health. Although the intention of this research is not to provide solutions for reducing $PM_{2.5}$ pollution, the paper analyzes the United States' experience with establishing $PM_{2.5}$ standards and mandates. Specifically, this paper focuses on the air quality control strategies adopted in California since the 1940s and draws parallels with present-day China. The research suggests that adequate government regulation, public awareness, regional collaboration and industrial compliance are keys to successfully controlling $PM_{2.5}$ pollution.

Keywords: $PM_{2.5}$; Smog; Air Quality Control; Multi-Pollutant Control; Coal Combustion; Vehicle Emission; Beijing; China

1. Introduction

Particulate matter ($PM_{2.5}$) particles are air pollutants with a diameter less than 2.5 micrometers, small enough to invade even the smallest of airways in human body. Particulate matter pollutant is composed of a mixture of microscopic solids and liquid droplets suspended in air. These pollutants are made up of a number of components, including SO_x, NO_x, NH_3, organic chemicals, volatile metals (e.g. mercury), soil or dust particles, and allergens (e.g. such as pollen or mold spores). When suspended in the atmosphere, $PM_{2.5}$ particles are the major cause of reduced visibility in major Chinese cities, such as Beijing [1]. Since 2008, the US embassy in Beijing has issued hourly readings of the $PM_{2.5}$ concentration on their Twitter feed [2], causing the Chinese Ministry of Environmental Protection to criticize the data as inaccurate, claiming it is a single data point that is not representative of the entire city of Beijing. This controversy, along with the increase in smoggy days in the Beijing area [3], believed to be caused by $PM_{2.5}$ pollutants [4], has led to increased local interest in $PM_{2.5}$ pollutants.

Unlike most air pollutants that consist of only one chemical compound, $PM_{2.5}$ particles consist of multiple compounds and are formed from primary and secondary participles [5]. Primary particles are formed during combustion, industrial processes and in natural processes (e.g. wind erosion). Secondary particles are formed indirectly through nucleation, condensation or processes where gaseous pollutants (SO_x, NO_x, NH_3, VOCs) are involved in particle formation or growth. Secondary sulfate and nitrate particles formed from SO_x or NO_x precursors are usually the dominant component in $PM_{2.5}$ particles. As a result of the chemical components in secondary participles, the environmental and health impacts from them are greater than from primary particles. Since $PM_{2.5}$ participles consist of multiple compounds, multi-pollutant controls are needed to reduce $PM_{2.5}$ pollutants [6]. This study is focused on identifying sources of the $PM_{2.5}$ pollutants observed in major Chinese cities and its effects on human health. Additionally, this paper will analyze the US air quality regulations, with a focused look at $PM_{2.5}$ regulation in California. The US experience in air quality con-

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trol will provide some thought leadership for air quality management in China.

2. Methodology

This paper was drafted through primary and secondary research. Primary research was conducted through interviews with environmental protection experts in China and the United States as well as analysis of historical data on $PM_{2.5}$ pollutant levels and regulations obtained through the US EPA's air quality control office. Secondary research was conducted through literature searches of journal articles, research reports, books, conference notes and news articles. News articles containing political opinions were excluded from the literature search. In addition, the authors also visited major Chinese cities to observe the smog first-hand. A workshop discussion was also held with environmental engineering professors at the Tianjin University of Technology. Data regarding the increased number of vehicles in Beijing, the increased production of coal and cement, and the increased residential construction were compared with the increased number of smoggy days in Beijing to illustrate potential sources of $PM_{2.5}$ particles. Lastly, the authors researched key events, legislation and approached adopted in California from 1940-2012 to control air quality. These approaches helped alleviate the smog issue in California and could be adopted by China in the future.

3. Results and Discussion

3.1. Smog and Major Sources of $PM_{2.5}$ Pollution

In 2012, there were 124 recorded smog days in Beijing [3]; in January 2013, there was 25 smoggy days, 13 days higher than the monthly average the previous years [7]. Areas adjacent to Beijing, such as Tianjin and Hebei Provinces, facing similar effects, have had over 100 smoggy days per year [8]. Research has shown that most high $PM_{2.5}$ events occur under a large surface high-pressure system, which causes air to sink on a large scale and traps pollutants and moisture near the surface [9]. These systems are often associated with light winds, which prevent particles from ventilating out of an area. Identifying which emissions or chemical processes are contributing to a certain city or county's particle pollution can be challenging. This makes PM a difficult pollutant to predict and control. Industrial sectors, such as automobile manufacturing, coal mining, construction and cement manufacturing, have grown significantly over the last 10 years. These sectors are known to generate large quantities of air pollutants, especially $PM_{2.5}$ particles.

3.1.1. Automobile Industry

Souring vehicle emission in China is one of major sources of $PM_{2.5}$. Vehicle emission can be a major contribution to smog because SO_x, NO_x, NH_3 and VOCs generated from vehicle exhaust can form secondary $PM_{2.5}$ particles. It has been reported that 41.8% $PM_{2.5}$ pollution in Beijing is contributed from vehicle exhaust [4]. In Beijing, from 1998 to 2012, the number of registered vehicles has increased by almost 4 million. As shown in **Figure 1**, in the last 10 years, the number of vehicles has more than doubled in Beijing. This is correlated to the increase in the number of smoggy days in Beijing [3,7]. Meanwhile, the population has increased from 12 million people to 20 millions in the last 10 years [10], but exhaust pollution has grown 10-fold. Although existing pollution sources have been treated, it can only be concluded that new pollution sources have emerged [11].

3.1.2. Coal and Industrial Processes

Coal combustion from utility and industrial boilers contributes significantly to $PM_{2.5}$ pollution [12]. China's heavy reliance on coal to fuel its power generation and industry processes, especially the use of poor quality coal, are likely to be the main cause. As shown in **Figure 2**, in the last 5 years, annual coal production has increased from 2.5 billion tons to 3.6 billion tons. Most of the coal is combusted directly from industrial boilers. Due to the lack of clean coal technology in China, a significant amount of primary and secondary $PM_{2.5}$ particles are

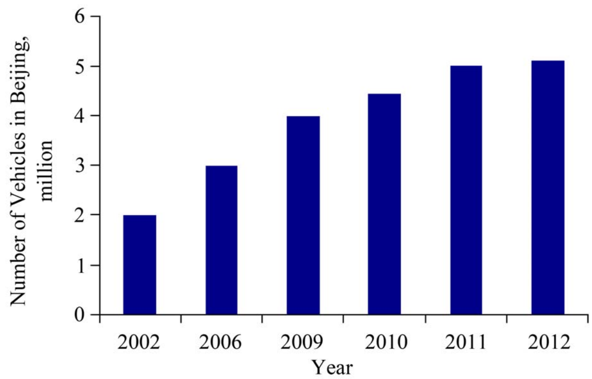

Figure 1. Increase of the number of vehicles in Beijing, China.

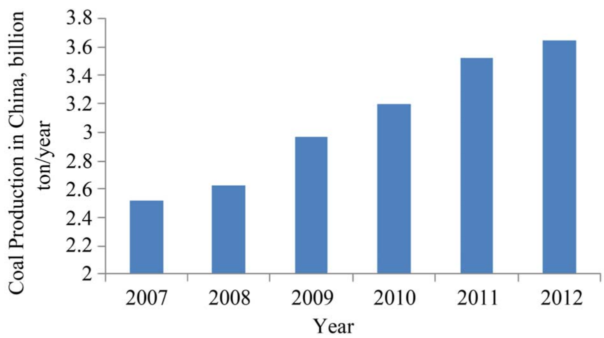

Figure 2. Increase in coal production output in China.

generated during coal combustion. It is reported that 36.4% $PM_{2.5}$ particles in the city of Beijing is contributed from coal combustion, and in suburban Beijing, coal combustion contributes 48.6% to $PM_{2.5}$ particles [4]. Although China has sought to impose strict fuel quality standards, experts say they are often circumvented. As long as penalties for pollution violations are mild, the enforcement of air quality control is nominal [9].

The smog effects have not been isolated to China—many other countries have experienced the same set of effects during their industrial boom periods. For example, many Japanese cities experienced the same problem, but with stricter enforcement of fuel and clean air standards, their long-term pollution problems are much less severe than China's today [13]. A research report comparing European and U.S approaches towards $PM_{2.5}$ particles control shows that in most western countries in the 1990's, the main contribution to $PM_{2.5}$ pollutants are sttionary combustion, industrial process, transportation and agriculture [14].

3.1.3. Construction and Cement Manufacturing Industry

The increase of population in Beijing stimulates housing industries. In the last few years, Beijing's residential construction has reached a total of 180 million square meters, generating 3.5 million tons of construction waste [15]. One-third of the wastes are generated from deconstruction of old apartments and re-build of new apartments within six districts of Beijing. Due to the lack of control on waste storage and transportation, some of construction wastes end up as blowing dust. Huang et al carried out research and developed models to estimate the amount of construction wastes contributing to blowing dust [16]. According to local environmental agency's analysis, residential and commercial construction wastes contribute 15.8% to $PM_{2.5}$ particulate in Beijing [15]. Cement is a major construction material. In China, the cement industry's boom began a decade ago, and with the fast growth of investment in capital assets such as housing and transport, investment in the cement industry reached 170 billion yuan in 2007 [17]. As shown in **Figure 3**, since 2000, cement production continues to increase at annual average growth rate of 7.7%. By 2006, China is the number one cement production country, producing 50% of the world's cement output. By 2012, total annual cement production reached 2.1 billion tons [18]. Cement manufacturing is a low efficiency and high polluting industry. In China, coal energy is used to manufacture cement and it is estimated that 7% of the annual coal produced is consumed by the cement industry. Coal combustion exhausts along with cement dust have been major sources of $PM_{2.5}$ pollution.

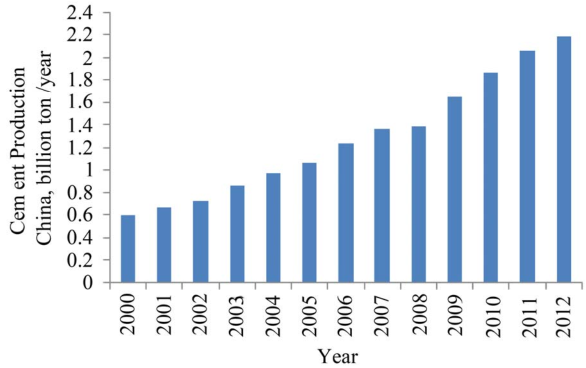

Figure 3. Annual cement production in China.

3.2. Impact of $PM_{2.5}$ Pollution on Human Health

In 1952, the "London Smog" epidemic led to the premature deaths of an estimated 12,000 people, who succumbed primarily to bronchitis, asthma, and respiratory distress within the two months following the event [19]. At the time, scientists understood very little about the adverse health effects of smog, but recognized the link between the precipitous rise in the death rate and the smog.

The chemical composition of particulate matter changes with size [5,6] and therefore, their effect on human health varies depending on the pollutant's size. The human body is unable to filter out small particulates [1] and as a result, dust and particulate matter that are smaller than 2.5 micrometers can enter into the alveoli in the lungs, where gas exchange occurs. These $PM_{2.5}$ particles negatively affect gas exchange within the lungs and can even penetrate the lung, escaping into the blood stream to cause significant health problems [20].

Health studies in the US and Europe have shown a significant association between exposure to fine particles and premature death from heart or lung disease. Fine particles can aggravate heart and lung diseases and have been linked to cardiovascular problems, cardiac arrhythmias, heart attacks, respiratory issues, asthma attacks, and bronchitis. These health issues can result in increased hospital admissions, emergency room visits, and school or work absences, and restricted activity. Additionally, older adults, children and individuals with existing heart or lung disease may be particularly sensitive to fine particle exposure [14].

China has just begun monitoring $PM_{2.5}$ pollutant levels and currently, there is no research data that correlates $PM_{2.5}$ pollution with various health issues. However in 2011, the China Daily newspaper reported that the lung cancer rate in Beijing had increased 60% over the past decade, even as levels of smoking had fallen, implying air pollution as a primary culprit for the increased cancer rate [11].

A joint study by Greenpeace East Asia and Beijing University's School of Public Health estimates that $PM_{2.5}$ pollution caused the cities of Shanghai, Guangzhou, Xi'an and Beijing a combined total of US $1.08 billion in economic losses over the past year. Greenpeace is calling for an urgent policy adjustment, including capping regional coal consumption, retrofitting De-NO_x for existing coal-fired power plants, and shutting down inefficient coal-fired industrial boilers. The report, "$PM_{2.5}$: Measuring the Human Health and Economic Impacts on China's Largest Cities", states that if these cities can effectively lower their $PM_{2.5}$ levels to meet the World Health Organization's Air Quality Guidelines, then premature deaths could be reduced by at least 81%, and economic losses for these four cities could be reduced by US $868 million [21]. A research report from Beijing University showed that effective implementation of $PM_{2.5}$ standards in major Chinese cities could result in health benefits estimated at billions of dollars [22].

3.3. US Approaches towards $PM_{2.5}$ Pollutant Control

3.3.1. US Regulation on Particulate Matter Pollutants

In 1997, the US Environmental Protection Agency (EPA), issued a fine particle standard of 65 μg/m^3, based on hundreds of health study evaluations and an extensive peer review process using the 3-year average of the 98th percentile concentration.

However, recent research on the health effects of particular matter has caused a revision to the National Ambient Air Quality Standards (NAAQS). During this revision, new pollutants with a diameter less than 2.5 μm, commonly called $PM_{2.5}$, is now regulated [23]. In 2006, the US EPA reissued their fine particle standard to a reduced level of 35 μg/m^3 [24].

At the time the fine particle standards were established in 1997, the US EPA also issued standard methods for monitoring fine particle levels in the ambient air to determine which parts of the country were subject to unhealthy levels. The US EPA deployed a nationwide network of more than 1200 monitors. Requiring 3 years worth of quality-assured data to create a revised particle standard meant that most sites did not have all the required information until mid-2003.

The designation process adopted by the US EPA has played an important role in identifying for the general public whether the air quality in a given area is healthy. In April 2003, the US EPA issued a memorandum outlining the schedule for designating areas under the $PM_{2.5}$ standard and related guidance on nine factors to consider in identifying nonattainment areas. The Clean Air Act provides for states to submit designation recommendations to the US EPA, and it requires the US EPA to provide time for consultation in cases where the administrator plans to promote a designation that modifies the state's recommendation.

The US EPA designates an area as nonattainment if it has violated the fine particle standards over a three-year period, or if relevant information indicates that it contributes to violations in a nearby area. The US EPA also may designate an area as attainment/unclassifiable, if: 1) monitored air quality data show that area has not violated the fine particle standards over a three-year period; or if 2) there is not enough information to determine the air quality in the area [25].

3.3.2. Air Quality Control Strategies and Practices Adopted in California

Early last century, smog was a concern to many industrialized countries such as the United States and the United Kingdom. It took a long time and dedicated efforts to solve smog problem in these countries. Today, in Beijing, the phenomena and the cause of smog are not that different from those occurred in western countries during industrialization: coal combustion, vehicle emission, industrial growth. The question should be posed as whether China can learn from the history and experience of other countries in particulate emission control.

The following analysis is based on records of key historical events and approaches adopted by State of California towards the air quality management [26].

As illustrated in **Table 1**, in 1940s, episodes of smog occurred in Los Angeles. Visibility was only 3 blocks and people suffered from watery eyes, respiratory discomfort and nausea. Today, Beijing's smog situation has many aspects in common with that of 1940's Los Angeles. As summarized in **Table 1**, it took more than half century for California to keep air quality under control. The key factors of success are highlighted as follow:

- Multi-Pollutant Control: smog is not simply caused by suspended particulates. Photochemical oxidants, sulfur dioxides, nitrogen dioxide, and carbon monoxide are the precursors of $PM_{2.5}$ particles which are major components of smog. California's experience indicates that $PM_{2.5}$ pollution control is not simply to reduce particulate emissions, it requires integrated control strategy for multi-pollutant control.
- Regional Control Approach: due to the nature of the air pollutants, especially long-distance transport phnomena of $PM_{2.5}$ particles, air quality management effort within a county or a city is ineffective. California's experience has shown that county-wide or interstate-wide collaboration is necessary.
- Government Function: dedicated efforts from state and local government are very important. California's governor signed into law the Air Pollution Control Act in 1940s. Meanwhile, investment in air quality control continues to increase.

- Regulate Energy Source: California has eliminated the use of coal, only allowing natural gas to be used as fuel for utility and industrial boilers.
- Vehicle Emission Control: regulation installed catalytic converters and mandated low-sulfur fuel for transportation
- Support Research and Scientific Discovery: state and federal government agencies invest in R&D to better control air pollution and develop viable technologies to reduce pollutants.
- Consistency of Policy: the success of quality control resides on having consistent policies, to which new mandates can be rolled out in phases that are built upon the success of earlier phases
- Compliance and Enforcement: in order to establish effective air quality control standard, California regulations have encouraged the public and industries to participate in public hearings. Typically, US industrial companies have environmental health and safety (EH & S) department to ensure compliance with government regulations. Violations can be extremely costly to industrial companies, and it is not uncommon that violations can result in bankruptcy.

3.4. Regulation, Technology Development and Prevention Strategies

Since 2011, public concern has led to calls for the Chinese government to establish a more stringent air quality policy that includes $PM_{2.5}$ control. Additionally, strong support exists for each provincial capital and municipality to begin monitoring $PM_{2.5}$ levels. As of January 2013, 74 Chinese cities have announced plans to publish $PM_{2.5}$ levels in real-time [27]. A long-term plan was announced by the Beijing municipal government in February 2012 to reduce annual average $PM_{2.5}$ concentrations to 35 μg/m^3. The plan calls for reducing $PM_{2.5}$ concentration to 60 μg/m^3 by 2015 and 50 μg/m^3 by 2020. In the future, China will increasingly face air pollution issues due to the rising consumption of fossil fuels. As a result,

Table 1. History of air quality control in california.

Year	Key Events and Approaches
1940-1943	California's (CA) population reached 7 million people. The number of registered vehicles approached 2.8 million. The first recognized episodes of smog occurred in Los Angeles. Visibility was only 3 blocks and people suffered from watering eyes, respiratory discomfort and nausea.
1946-1947	Raymond R. Tucker studied the Los Angeles area's smog and recommended that county-wide collaboration was needed. CA governor signed into law the Air Pollution Control Act.
1950-1952	Dr. Arie Haagen-Smit discovered the nature and causes of photochemical smog. He determined that nitrogen oxides and hydrocarbons in the presence of ultraviolet radiation from the sun forms smog.
1955	Federal Air Pollution Control Act of 1955 was enacted, providing for research and technical assistance and authorizing the Secretary of Health to work towards a better understanding of the causes of air pollution. Los Angeles County Motor Vehicle Pollution Control laboratory began within the Los Angeles APCD.
1960-1963	CA's population reached 16 million and registered vehicle approached 8 million. The first Federal Clean Air Act of 1963 was enacted and the first automotive emission control technology was mandated in California.
1969-1970	Air Quality Standards were set by the new Air Resources Board (ARB) for total suspended particulates, photochemical oxidants, sulfur dioxides, nitrogen dioxide, and carbon monoxide. CA's population reached 20 million and registered vehicle reached 12 million. The US Environmental Protection Agency (EPA) was created to protect all aspects of the environment.
1975	The first two-way catalytic conversions came into use as part of Air Resources Board's (ARB) motor vehicle emission control program. The California Air Pollution Control Officers Association was created.
1980	CA's population reached 24 million and registered vehicle approached 17 million. ARB limited lead in gasoline. Federal Clean Air Act amendments of 1977 were enacted.
1984	CA Smog Check Program went into effect identifying vehicles in need of maintenance
1988	CCAA was signed by governor. The act set forth the framework for how air quality will be managed in California for next 20 years.
1990-1992	Phase I CA cleaning burn gasoline came to market. The CAA Amendment of 1990 were signed into law by President Bush
1994	US Court ordered US EPA to develop Federal Implementation Plan for numerous non-attainment areas in CA.
1998	ARB identified diesel particulate emissions as a toxic air contaminant. CA's Phase II Cleaner Burning Gasoline came to market.
2001-2004	ARB adopted new particulate matter standards. The new annual average for $PM_{2.5}$ is 12 μg/m^3. New rules that limit public exposure to asbestos-laden dust from construction sites. Population reached 34 million and registered vehicle approached 23.4 million.
2006-2007	CA switched to new low sulfur diesel fuel. Auto manufacturers must label vehicles to reflect smog and greenhouse gas emissions. Adopted greenhouse gas emissions limit to reflect 1990 levels.
2009-2010	ARB adopted the Low Carbon Fuel Standard. Adopted the Renewable Energy Standard. One third of the electricity sold in the state in 2020 will come from clean and green sources of energy.

strengthening air pollution control policies has become increasingly necessary not only for coal-based power plants, but also for other sectors.

Based on California's experience, air pollution control requires collaboration among the governments of affected regions [28]. Regulating $PM_{2.5}$ pollutants in Beijing alone will not solve the smog issue. Instead, establishing regional air quality management coordination systems in developed cities such as Beijing and its surrounding suburbs will be necessary [29]. With the rapid urbanization and economic development in China and the resulting rise in air pollutant emissions, there is a need to establish regulations to limit air pollutant emissions.

Currently, China lacks research on $PM_{2.5}$ reduction technologies and strategies. Research and development into technology to reduce air pollution and promote air quality improvement needs to be established. In the United States, while there are no smog issues on the scale of the problem in Beijing, the Clean Air Interstate Rule has been established to invest US $41 billion in R&D to reduce air pollution in 108 hot spots. One possible future area of innovation is in using weather data to forecast $PM_{2.5}$ levels. However, more research needs to be conducted on $PM_{2.5}$ forecasting and its application on public health.

In Beijing, another future area of innovation is in reducing vehicle emissions. The correlation between vehicle emission levels and air pollution is widely recognized. Improving fuel quality, including reducing the sulfur content in fuel oil, is an important step towards reducing toxic vehicle emissions.

Further research also needs to be conducted to determine best practices for protecting the public from high pollutant levels. Public health recommendations need to be tested for efficacy and should balance protection with practicality. For example, recommending the general public to limit their outdoor recreation during high pollutant days may not be practical and instead, recommendations may need to be targeted at high-risk groups (e.g. the elderly). Recommendations must also be economically feasible. For example, while buying an expensive air purifier may help, this recommendation would only be feasible for a minority of the population [30].

4. Conclusion

$PM_{2.5}$ particles are dangerous pollutants that are harmful to human health and have the potential to destroy the environment. Most $PM_{2.5}$ particles, especially those containing sulfates, nitrates, and many organic compounds, are created through secondary industrial and manufacturing processes. Characterizing the chemical reactions that take place in the atmosphere to determine the source of fine particles is complicated. As a result, it is a challenge to attribute secondary particle formation to specific emission sources. In Beijing, China, the high frequency of smoggy days is strongly associated with levels of $PM_{2.5}$ pollutant. Major sources of $PM_{2.5}$ include vehicle exhaust, coal combustion from the utility industry and industrial processes, and the housing construction industry, including the cement manufacturing process. Stringent, government-mandated and integrated multi-pollutant control strategy, and regional control approaches have been shown to be very effective in California air quality management. Adequate government regulation, public awareness, regional collaboration and industrial compliance are the keys to successful control of $PM_{2.5}$ pollution and smog.

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