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Tiered transferable pollutant pricing for cooperative control of air quality to alleviate cross-regional air pollution in China

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ABSTRACT

Cross-regional air pollution is a widespread concern worldwide. This problem is particularly acute in China, where it has caused a substantial public health crisis. We consider the problem of determining tiered transferable pollution price control for air quality based on a piecewise transfer cost. Under tiered pricing, the more pollution that is transferred, the higher the transfer cost per pollution unit that must be paid. The tiered transferable pollutant pricing (TTPP) control problem is first formulated as a bi-level mathematical program model in which the upper level consists of China's Ministry of Environmental Protection, which controls air pollution using a tiered transferable pollution price, and the lower level is represented by a group of administrative regions that aim to relieve pollution with respect to their generalized costs, including reduction and transfer costs. Based on optimal conditions, the TTPP control problem is theoretically reformulated as the minima of a solution set for a sequence of equations. Each equation sequence is structured such that all of its components are optimal reactions of the lower-level regions. Then, we apply a bisection-based algorithm to solve the sequence of equations. Finally, we use the pollutant SO_2 control problem in the Beijing-Tianjin-Hebei delta as a numerical example to provide insight into the model and performance of the algorithm. The results reveal that all regions in that delta can benefit from the tiered transfer pricing scheme, which also implies that the scheme has potential for practical application.

1. Introduction

In January 2013, smog suddenly shrouded 15 adjacent administrative regions, covering more than 1.8 million square kilometers of Eastern China. This large-scale cross-regional air pollution resulted in the closure of six major highways. Airports ceased operations, and approximately 600 million individuals were affected. During the smog event, eight cities that encircle China's capital Beijing and Beijing's neighboring provinces of Tianjin and Hebei were listed as the worst 10 Chinese regions for air quality. The deteriorated air quality had become a public health crisis while goals of the "13th Five Year Plan" (2010–2015) issued by China's State Council, which only considers the total quantity of pollution in Beijing, Tianjin and Hebei, were considered fully achieved. This contradiction suggested that current standards lacked rigor. In addition, it suggested that air quality should be regarded as a key environmental indicator in practical pollution control. Recognizing these implications, in 2015, Liu Bingjiang, the senior administrative official of China's Ministry of Environmental Protection (MEP) stated, "We should no longer merely consider the total amount of pollution quantity reduction in pollution control" and stressed that "A bridging mechanism between the current total quantity reduction and quality improvement should be urgently established". Subsequently, a variety of measures focused on air quality, such as plant shutdowns, an odd-even car ban, and the interruption of construction site operations, were initiated to improve air quality when the MEP determined a high air quality index (AQI). The AQI is a technical assessment of air pollution that is performed and announced daily (Table 1; http://www.mep.gov.cn/hjzl/). Despite these efforts, the cross-region air quality remains unimproved.

Economic means represent a widely used approach to pollution control. Crocker (1966) and Dales (1968) proposed a transferable discharge permit system to share the pollution-control burden among sources. Montgomery (1972) proved that such a system could provide a cost-effective policy instrument. Montero (2002) compared the environmental incentives of various pollution control measures. Using experimental simulations, Murray and Rivers (2015) proved that

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Table 1
Air quality index classification standards.

Pollution grade	Air quality	SO_2 concentration (Unit: mg/m^3)	Health concern
I	Excellent	0.000–0.050	Air pollution poses little or no risk.
II	Good	0.051–0.150	A moderate health concern for an extremely small number of people.
III	Mildly polluted	0.151–0.800	Most people are unlikely to be affected, but older adults and children are at increased risk. People with lung disease are at a greater risk when ozone reaches this level. Those with heart and lung disease are at increased risk when particulates reach this level.
IV	Moderately polluted	0.801–1.600	Everyone may begin to experience some adverse health effects. Sensitive groups may have more serious effects.
V	Heavily polluted	Higher than 1.601	This category triggers a health alert, meaning everyone may have more serious health effects.

carbon taxation could significantly reduce emissions although such taxation was initially opposed by the public. Hahn (1984) argued that successfully allocating scarce resources by means of the market is largely based on the assumption that the market will approximate a competitive ideal. Incomplete information easily results in individual participants monopolizing the emissions market, which weakens pollution control efficiency (Misiolek and Elder, 1989). Escobedo et al. (2011) subsequently proposed that social and economic common interests should be considered when developing measures to mitigate air pollution. Luechinger (2010) found that air pollution had significantly negative impacts on life satisfaction and would eventually involve a willingness to pay for air pollution control. These findings imply that only when all involved parties can benefit from pollution control measures are they likely to be successfully implemented.

Engineered biological systems represent another way to alleviate pollution. Iranpour et al. (2005) compared the requirements of biofilters and biotrickling filters with respect to their use to address complex air pollution. Abraham et al. (2015) proposed that waste treatment plants could remove odors using shell biofilters. Biological waste air can be purified by ecological technology (Delhoménie and Heitz, 2005; Mudliar et al., 2010). For any enterprise, the quality of its biological waste treatment system should be evaluated based on its ability to decrease pollution. Based on a given ability to treat pollution, how decision-makers should formulate a pollution reduction plan is considered in this paper.

At present, China's MEP implements a territorial total-quantity reduction scheme for pollutant discharge as a means to control air pollution. Under this scheme, each administrative region is only concerned with its own pollution control objective and deals with its own pollution individually because the reduction control scheme only forcibly stipulates the maximum discharge standards for each administrative region. However, the results of unassisted reduction measures can be easily offset by an excessive pollution discharge by one or more other nearby administrative regions. Consequently, the total-quantity reduction mechanism is hard-pressed to fundamentally solve the cross-regional air pollution problems because of the contradiction between the boundedness of administrative divisions and the unboundedness of the natural atmosphere (Friedlander, 1977; Arya, 1999; Zannetti, 2013). Employing sensitivity analysis, Wang et al. (2014) assessed the interprovincial impacts of emissions reduction in Beijing-Tianjin-Hebei and the Yangtze River Delta and indicated the necessity of cooperative control for cross-region air pollution. Recently, Zhao et al. (2013) developed the quantitative analysis and modeling of a unified transferable pollutant price scheme for cooperative control of China's cross-regional pollution. With the scheme, the imposed ultimate maximum environmental discharge standard was established while considering the unboundedness of natural resources. Unfortunately, although the entire area's pollution control objective was obtained using the model, the environment has been damaged as a result of excessive pollution caused by regional transfer. Under unified pricing, no matter how seriously the environment is damaged by transferred pollution, the marginal transfer cost is uniform. This outcome implies that this approach would weaken regional initiatives to mitigate individual-region pollution. For example, if the unified transferable pollutant price is too low compared with the marginal reduction cost of a given region, the region is likely to transfer its pollution and depend on other regions to reduce it.

In this paper, we intend to advance this approach an additional step by proposing a tiered transferable pollutant price scheme for air quality to alleviate China's cross-regional air pollution. Tiered pricing schemes are typically applied to regulated products, such as water, electricity or access to new medicines (Zeng et al., 2011; Du et al., 2015; Moon et al., 2011). Tsao et al. (2017) demonstrated that two-tiered pricing is better than one-tiered. Sun and Yan (2015) and Schoengold and Zilberman (2014) investigated the effect of tiered pricing for household electricity on achieving the twin objectives of efficiency and equity. The results of these studies are highly useful to our application of tiered transferable pollutant pricing in pollution control. In the remainder of the paper, we first describe our tiered transferable pollutant pricing scheme. Then, to reflect the differences in unit transfer costs caused by differing amounts of transferred pollution, we introduce a piecewise linear transfer cost function. Through this function, we observe that the more pollution that is transferred to other regions, the higher the unit transfer cost is for the transferring region. In view of the mobility of the atmosphere, we advocate the cooperative control of pollution and regard all relevant regions in the polluted area together in an integrated whole. Then, we construct a mathematical optimization model and devise a bisection-based algorithm to solve the model. Finally, we use SO_2 reduction in the Beijing-Tianjin-Hebei Delta cross-region as an example to illustrate the validity and effectiveness of the proposed method. Our numerical results indicate that the tiered transferable pollutant pricing scheme is superior to the current total-quantity reduction scheme and the unified transfer tax. This outcome implies that the tiered pricing scheme may be used as a theoretical reference to guide the resolution of China's cross-regional pollution problem.

2. Description of the TTPP model for cross-regional air pollution control

We consider China's cross-regional air pollution problem based on an underlying complete directed graph $G(I, T)$, where $I = \{1,2,\cdots,|I|\}$ denotes the set of nodes with cardinality $|I|$ (i.e., the number of administrative regions involved in the polluted area), and T denotes the set of arcs with cardinality $\frac{|I|\cdot(|I|-1)}{2}$. A node represents an administrative region that can potentially transfer pollutants to or from other administrative regions. The arc set T denotes the pollutant quantity transferred between each pair of administrative regions. That is, $T = \{ T_{ik} \mid T_{ik}$ is the quantity of some pollutant of region i transferred to region k, where $T_{ik} \geq 0$, or the quality of some pollutant of region i transferred from region k, where $T_{ik} \leq 0, i, k \in I$ and $k \neq i \}$. The structure of the air pollution across administrative boundaries in the polluted area is shown in Fig. 1.

For any region i, $i \in I$, the region initially produces the quantity of some pollutant p_{0i} annually. To achieve the environmental reduction goal for region i, $i \in I$, by discharging a quantity lower than p_{imax} prescribed by

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