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Productivity Loss amid Invisible Pollution¹

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Abstract

Ground-level ozone is a continuing problem worldwide, but research on the influences of ozone pollution on labour productivity in developing countries is insufficient. We investigate the effect of ozone pollution on outdoor worker productivity in the service sector using a unique panel dataset of courier productivities from a top five express company in China. Using an instrumental variable constructed from ozone pollution of upwind nearby cities, we find that a one-standard-deviation increase in daily ozone pollution decreases courier productivity by 8.91%. The same increase in ozone in the previous 30 days decreases worker productivity by 37.9%.

Keywords: ozone pollution, air pollution, labour productivity, outdoor workers, contemporaneous effect, cumulative effect, express delivery industry

JEL codes: J24, O13, P23, P28, Q51, Q53

1. Introduction

Ground-level ozone pollution is a continuing challenge in developed countries and a growing problem in developing countries (Health Effects Institute 2019). Recognized worldwide as a major health hazard, acute exposure to ozone may cause damages to respiratory and cardiovascular health (Kim et al. 2011; Day et al. 2017), thus decreasing the labour productivity and welfare of outdoor workers.¹ Despite mounting research on the productivity effects of particulate matter (PM) (Chang et al. 2016; Archsmith et al. 2018; He et al. 2019), we still do not know enough about the influences of ozone on outdoor labour productivity in developing countries, where most of the attention on air pollution control is paid toward PM_{2.5} reductions. In addition, air pollution control in fast-growing regions may require coordinated management of various air pollutants. For instance, recent scientific evidence suggests that the decrease in PM_{2.5} in China has slowed down the aerosol sink of hydroperoxyl radicals, thus stimulating ozone production (Li et al. 2019). Therefore, if ozone pollution is found to significantly decrease worker productivity, policy makers should pay attention to vulnerable populations so that people can take precautionary measures and enact efficient pollution control policies that account for the two-pollutant problem, thus reducing the overall socioeconomic cost of air pollution.

This study investigates the contemporaneous and cumulative effects of ozone pollution on outdoor workers using a unique panel dataset on the daily productivity of couriers from a top five express company in China.² Estimation of the productivity effects of ozone pollution has been impeded by a paucity of productivity data of the vulnerable population, i.e., workers in the outdoor environment, as well as the coexistence of multiple pollutants. Records of the daily delivery volume at the courier level are used to determine employee salaries and are of high quality, which provides an advantageous

¹ Ozone concentrations in airtight buildings with doors and windows closed can be much lower than the outdoor concentration of ozone.

² The identity of the company needs to be protected.

context for examining the effects of ozone pollution on the productivity of outdoor workers. These data can be made open access after anonymization and desensitization. In addition, our dataset covers 18 cities in Guangdong Province that have long been notorious for ozone pollution during the summer. In the sample, ozone is the primary air pollutant for 80% of days (Table 1) and the only contributor for days with an air quality index (AQI) exceeding 117 (Appendix Table 1).³

Omitted variables and measurement errors of the pollution variable often arise in research that estimates the socioeconomic effects of air pollution (Arceo et al. 2016). Avoidance behavior of the couriers in China is limited due to the typical outdoor working environments that are not equipped with air purifiers or air conditioners, the invisibility of ozone pollution, and low awareness of the effective protective measures to prevent ozone inhalation (to be explained in Section 2).⁴ Considering that couriers may shift working hours within a day to avoid severe ozone pollution, the OLS estimates should be viewed as being inclusive of this adjustment margin. On the other hand, measurement errors may bias the estimated effect of ozone pollution on labour productivity downward, which can be exacerbated in the fixed effects model.

Based on scientific evidence that long-range transport of ozone and its precursors may occur over several hundred kilometers (Kato et al. 2004; Gao et al. 2016; Zhang et al. 2019), we construct an instrumental variable (IV) for local ozone pollution using ozone concentrations of upwind nearby cities, which corrects the biases from measurement errors and omitted variables. The IV estimation results show that a one-standard-deviation increase in daily ozone pollution significantly decreases courier productivity by 8.91%, conditional on individual fixed effects, month fixed effects, day-of-week fixed effects, and rich weather characteristics. As a comparison, the OLS estimate is

³ AQI is calculated as the individual air quality index of the primary air pollutant.

⁴ Ground-level ozone is a colorless and highly irritating gas. People can only avoid the harmful effects of ozone to health by staying in nonleaky buildings or wearing masks with activated carbon (China CDC 2019; Zhang et al. 2019).

1.69%. We also construct the IVs for five other air pollutants using the aforementioned method and simultaneously estimate the effects of ozone and the other air pollutants. These specifications still yield highly significant negative effects of ozone on courier productivity, whereas we do not find any significant effect of the five other air pollutants on courier productivity. Couriers are required to work under a routine schedule, and ozone pollution does not affect worker attendance significantly, which further suggests that the negative effect of ozone results from productivity changes on the intensive margin. In addition, IV estimates from the distributed lag model reveal that the same increase in ozone over the previous 30 days significantly decreases the courier productivity by 37.9%.

This study contributes to the existing literature in three aspects. First, it is among the first to investigate the causal effects of ozone pollution on worker productivity in developing countries using high-frequency individual productivity data from real working environments. Our IV estimate of the ozone pollution effect is much larger than the OLS estimate; this indicates the necessity of addressing the biases from the measurement errors of air pollution and omitted variables when using data from developing countries. We also point out that estimates obtained in the context of developed countries should not be simply extrapolated to developing countries, where ozone pollution can be much higher, because a nonlinear dose–response function between pollution and socioeconomic outcomes may exist (Arceo et al. 2016). Our study is close to Graff Zivin and Neidell (2012), which estimates the effect of ozone on the productivity of agricultural workers in the US. The average ozone concentration of $101.46 \mu\text{g}/\text{m}^3$ in this study is several times higher than the $26.48 \mu\text{g}/\text{m}^3$ in Graff Zivin and Neidell (2012). Moreover, despite the literature on the productivity effects of PM (Chang et al. 2016; Archsmith et al. 2018; Adhvaryu et al. 2019; He et al. 2019; Heyes et al. 2019), the biological and medical mechanisms of how PM and ozone can impair human health may still differ due to their respective properties. Overall, this study enriches the

research on the socioeconomic effects of ozone pollution in highly polluted, fast-growing areas.

Second, although medical studies suggest that long-term exposure to ozone may increase the risk of death from respiratory causes, evidence of the causal relationship between long-term ozone exposure and many health outcomes is insufficient (US EPA 2020). Some economic studies have estimated the cumulative or long-term effects of PM on labour productivity in the manufacturing sector (He et al. 2019; Fu et al. 2018; Hansen-Lewis, 2018). However, to the best of our knowledge, this study is the first to use a causal inference framework to estimate the cumulative effects of ozone pollution on worker productivity and the extent of long-term adaptation to ozone pollution. In addition to the large decrease in worker productivity from cumulative exposure to ozone pollution in the short term, couriers who work in the hometown suffer a significantly lower productivity effect of ozone than those who do not, which suggests a long-term adaptation to ozone pollution.

Third, this analysis adds to the literature on ways of improving worker productivity. Existing studies have examined the effectiveness of incentive schemes, more flexible workplace regulations, and temperature adjustments (Lazear 2000; Pilcher et al. 2002; Bandiera et al. 2005; Bloom et al. 2014). The present study suggests that ozone pollution control can significantly improve outdoor worker productivity in developing countries.

This study focuses on the rapidly developing express industry, which is an important component of the service sectors and national economies of both developed and developing countries. Around the world, last-mile delivery is becoming more crucial as the demand for high-end, time-sensitive goods increases. From 2015 to 2020, global consumer spending on delivery services had an average growth rate of 6.1%.⁵ In 2019, the express industry in China delivered over 63.5 billion pieces (more than any other country), hired more

⁵ Global Courier and Delivery Services Industry - Market Research Report:
<https://www.ibisworld.com/global/market-research-reports/global-courier-delivery-services-industry/>

than 3 million employees, and earned 107.96 billion USD in revenues (State Post Bureau of China 2019). Our conservative calculations show that in 2019, ozone pollution reduced the incomes of express delivery couriers in China by more than 276.14 million USD. Given the growing economic importance of the express delivery industry, e-commerce, and service sectors in many developing countries, our study of the effects of ozone pollution on courier productivity has significant practical implications.

Existing relevant research on the service sectors in developing countries has focused on workers in indoor environments (Chang et al. 2019; Huang et al. 2020; Kahn and Li 2020), but similar studies are also needed for the many outdoor workers worldwide. For instance, 37.2% and 81.4% of people in urban and rural areas of China, respectively, still work outdoors or in non-climate-controlled environments.⁶ In outdoor working environments that are not equipped with air purifiers, relevant workers are especially susceptible to ozone pollution. The need for both physical strength and mental skill makes the job of courier similar to many other outdoor jobs such as food delivery, outdoor maintenance, construction, and agricultural work. Moreover, compared with couriers who drive an electric tricycle to deliver packages, other outdoor jobs may impose higher requirements on manual labour, which suggests even larger productivity and welfare losses for relevant outdoor workers.

The rest of this paper is organized as follows. Section 2 introduces the background of the courier job and ozone pollution in China and explains in more details why our data set in Guangdong Province offers a useful setting for analyzing the productivity effects of ozone pollution. Section 3 introduces the data and summary statistics. Section 4 describes the empirical models. Section 5 illustrates the estimation results, which are compared with the existing literature, and presents the welfare effects of ozone pollution. Section

⁶ The numbers are calculated from the 2016 survey data in China Labor-force Dynamic Survey, which were collected by Sun Yat-sen University.

6 concludes this paper.

2. Background: Courier Job and Ozone Pollution in China

We collect the data on individual labour productivity of couriers from *T* express company, which is one of the top five companies in the express delivery industry of China. *T* express company has multiple subsidiaries in Guangdong Province. Each subsidiary randomly assigns its couriers to different branches, and one courier is responsible for a specific branch area. Packages with recipient addresses within a branch area are then assigned to the responsible courier for distribution. A courier works for the same branch in the sample period.

Couriers have a routine working procedure every day. In the morning, couriers sort the packages; prepare the work tools, including the courier car, the handling cart, and the package scanner; and deliver the packages to customers. Right before arriving at each destination, the courier confirms the preferred receiving method and location of the recipient via phone calls. If the recipient is absent, the courier usually leaves the package in front of the door or at the community package storage place and notifies the recipient via calls or messages.⁷ If the recipient is present or strongly prefers to sign for the package in person, then the courier usually waits for him/her to show up. A bar code on each package helps record and trace the location of a package in the postal transportation network. Once a package is delivered, the courier scans the bar code, and the delivery information is immediately recorded in the electronic information system of the company and sent to the package recipient. At the end of the day, the courier comes back to the branch and returns the work tools and the undelivered packages. Overall, the courier job requires physical strength and mental skills of accuracy, communication, and management.

⁷ In China, each community usually has a package storage place where residents come to pick up packages.

The salary of couriers usually comprises a considerably low base salary and a piece-rate salary. The courier will earn a higher daily income if additional packages are delivered on that day. In addition, each company is concerned with its reputation with customers because of the fierce competition of the express industry in China. If the delivery of a package is considerably long, a package is sent to the wrong place, or a package is lost due to the mistakes of the courier, then the customer can submit complaints to and claim compensation from the express company.⁸ The courier must then find the package and send it to the right place immediately; otherwise, the company has to compensate for the loss of the customer. Either situation results in a lower income for the courier. However, the courier has flexibility in selecting the pace of distributing packages.

Existing controlled human exposure and experimental animal studies find that short-term exposure to ozone at low and moderate levels is associated with reduced lung function, respiratory symptoms, increased airway responsiveness, mild bronchoconstriction, and pulmonary inflammation. Thus, ozone makes it difficult for humans to breathe deeply and vigorously as they normally would and can reduce the metabolic rate (Lippmann 1989; Kim et al. 2011; US EPA 2020). Short-term ozone exposure at levels not correlated with lung function changes is also associated with platelet activation and blood pressure increases, suggesting that ozone may affect cardiovascular health (Day et al. 2017). Additionally, increased levels of ozone are correlated with an increased rate of cognitive decline (Cleary et al. 2018). Therefore, ozone pollution may decrease the productivity of outdoor workers.

Data on labour productivity of couriers in Guangdong Province of China offer an advantageous context for examining the effects of ozone pollution on the individual labour productivity of outdoor workers. First, although the Chinese central government did not pay enough attention to ozone pollution

⁸ Expressing user experience and complaints about express delivery service is easy for Chinese customers through phone calls and electronic business platforms, such as *world.taobao.com*.

regulation until recent years, high ozone episodes were frequently observed in Guangdong Province in as early as 1995, and ozone has been the primary air pollutant in Guangdong (especially the Pearl River Delta (*PRD*) region) for many years (Yang et al. 2019). In 2016, ozone was the primary air pollutant for 42.7% of days in Guangdong, which exceeds the percentage of 31.6% for PM_{2.5}. In addition, in our study period of July 1 to September 30, 2016, ozone was the primary air pollutant for 80% of the days, whereas each of the five other air pollutants (PM_{2.5}, PM₁₀, SO₂, NO₂, CO) was the primary air pollutant for at most 9% of days (Table 1). We also calculate the maximum individual air quality index (IAQI) for ozone, PM_{2.5}, PM₁₀, SO₂, NO₂, and CO based on the summary statistics of the six air pollutants and the calculation formula of IAQI.⁹ The maximum IAQIs of ozone, PM_{2.5}, PM₁₀, SO₂, NO₂, and CO are 207, 116.3, 87.5, 46, 83.8, and 42.5, respectively (Appendix Table 1). Thus, the values of AQI that exceed 117 result from the high concentrations of ozone instead of any other pollutant.¹⁰ These facts suggest that ozone is mostly responsible for the larger values of AQI in this study.

Second, among all the provinces in China, Guangdong Province has the largest delivery volume and the highest revenue in the express industry (Appendix Figure 1). In addition, records of the daily delivery volume of each courier, which are used to determine their salaries, are of high quality. Interviews with the company manager, the HR director, and multiple frontline couriers show that courier work has been in high demand in Guangdong for many years; thus, the life of a courier is highly fast-paced. Couriers usually drive a simple electric tricycle, which is approximately 3 m long, 1 m wide, and 1.7 m high, to transport the packages in the city (Appendix Figure 2). The

⁹ The calculation formula of IAQI is as follows: $IAQI_P = \frac{IAQI_{High} - IAQI_{Low}}{BP_{High} - BP_{Low}} (C_P - BP_{Low}) + IAQI_{Low}$.

$IAQI_P$ is the individual air quality index for a pollutant. C_P is the pollutant concentration. BP_{Low} is the concentration breakpoint that is $\leq C_P$. BP_{High} is the concentration breakpoint that is $\geq C_P$.

$IAQI_{Low}$ is the index breakpoint corresponding to BP_{Low} . $IAQI_{High}$ is the index breakpoint corresponding to BP_{High} . When multiple air pollutants are measured, AQI is defined as the maximum of the IAQIs. Appendix Table 1 displays the concentration and index breakpoints for the six air pollutants.

¹⁰ The calculation method of AQI has already accounted for the relative molecular mass and harmfulness of different air pollutants.

uniform capital input for the courier job largely removes the omitted variable bias when such input is not included in the regressions.

Third, couriers in China are typical outdoor workers in developing countries, who are unlikely to adopt effective avoidance behavior. Courier cars are not equipped with air conditioners or air purifiers. Similar to many other outdoor workers, couriers do not wear masks to protect themselves from air pollution during working hours. Additionally, the only effective way of avoiding the health damages of ozone is to remain indoors during high pollution hours or wear masks with activated carbon (China CDC 2019). We collect the Baidu search index of “masks” and “masks with activated carbon” as proxies for the intention of avoidance behavior to deal with air pollution and ozone pollution, respectively, and use the index of “job searching” as the benchmark.¹¹ Appendix Figure 3 shows that the index value of “masks with activated carbon” is approximately half of the values of “masks”, and is much lower than the index value of “job searching”. This suggests that awareness of the effective protective measures in response to ozone pollution for our study area is low.

3. Data

T company provides a random sample of the daily delivery volumes of its couriers at 39 subsidiaries in 18 prefecture-level cities of Guangdong Province from July 1 to September 30, 2016.^{12 13} Although *T* company does not provide detailed information on daily working hours, couriers are required to work under a routine schedule based on a discussion with the management team. Therefore, all couriers are assumed to work the same hours on each day. From 36,496 observations of 649 couriers, which account for 55% of the

¹¹ The Baidu search index is one of the best ways of determining the degree of concern on certain issues of Chinese web users. Baidu is the largest and the most frequently used Chinese search engine by the Chinese people. Baidu search index is similar to Google Trends (GT). Google is blocked by the Great Fire Wall. Thus, GT data are unavailable for research.

¹² The weight of each package is unavailable for research.

¹³ A prefectural-level city is an administrative division that ranks below a province and above a county in China’s administrative structure. Subsidiaries in the cities of Heyuan, Yangjiang, and Zhaoqing did not provide sufficient information on the productivity of couriers and are excluded from this analysis (Appendix Figure 4).

entire sample, we are able to collect the demographic characteristics of each courier, including gender, age, years of education, years of working, whether his/her *Hukou* is in Guangdong Province (a proxy for a local resident or not), and whether the courier works in his/her hometown.¹⁴

Appendix Table 2 shows the number of couriers and the average daily delivery volume per courier in each city in the sample. Couriers are unevenly distributed, and the average daily delivery volume per courier differs across space, which emphasizes the importance of controlling for city-level fixed effects. Figure 1 displays the distribution of individual daily labour productivity in the dataset. Panel A is a histogram of the daily delivery volume across couriers over different days, which suggests a large variation in individual labour productivity. Estimating the effects of ozone pollution on the log of courier productivity is an appropriate fit for the data because the histogram has a relatively long right tail. Panel B is a histogram of the average labour productivity over the sample period across different couriers. On average, a courier delivers 102 pieces per day, while some couriers deliver over 200 pieces per day. Panel B demonstrates a large difference in labour productivity across couriers and the importance of controlling for individual heterogeneity. Panel C is a histogram of the average daily delivery volume per courier across different days, and Panel D displays the average delivery volume per courier on each day. Panels C and D demonstrate a large variation in courier labour productivity across days, which emphasizes the importance of controlling for common time effects.

We collect daily concentrations of ozone (maximum 8 hour average), PM_{2.5}, PM₁₀, NO₂, SO₂, and CO, and daily values of air quality index (AQI) for each city in Guangdong Province from the National Environmental Monitoring Center of China. We also collect air pollution concentrations of the nearby cities in other provinces, which are used to construct the IVs for the air

¹⁴ *Hukou* is a system of household registration used in mainland China. A household registration record officially identifies a person as a permanent resident of an area and includes identifying information such as name, parents, spouse and date of birth.

pollution levels of several cities in Guangdong. Ozone is considerably higher during the daytime and decomposes quickly at night. Thus, we estimate the effect of daily maximum 8 hour average concentration of ozone, which better captures the accurate concentration of ozone during working hours than the daily average concentration of ozone. As explained in Section 2, ozone is mostly responsible for the larger values of AQI in the sample. In addition, the correlation coefficient of AQI and ozone (0.956) is considerably higher than those of AQI and the other air pollutants (Appendix Table 3). Therefore, for each regression, we also estimate the effect of AQI as robustness checks.

We collect rich weather characteristics for two reasons. First, weather variables, which are correlated with ozone pollution and may directly influence the labour productivity of individual workers (Jayamurugan et al. 2013; Somanathan et al. 2018), should be controlled to minimize the omitted variable bias. For instance, ozone is created by the chemical reactions between nitrogen oxides (NO_x) and volatile organic chemicals (VOC) in the presence of heat and sunlight (UV radiation), and high temperature and solar radiation may directly influence courier productivity. Second, wind direction and speed are used to construct the IV for local air pollution. Therefore, we collect daily maximum temperature, precipitation, average relative humidity, atmospheric pressure, and hourly maximum wind speed and direction for each city from the Guangdong Meteorological Bureau (GMB). We also collect solar radiation data from the fifth-generation European Center for Medium-Range Weather Forecasts atmospheric reanalysis of the global climate (ERA5), which provides hourly data of top net solar radiation at the spatial resolution of $0.25^\circ \times 0.25^\circ$.¹⁵ We first sum the hourly solar radiation in each day for each grid and then calculate the daily average solar radiation by averaging across all grids in each city to calculate daily solar radiation at the city level.¹⁶ Finally,

¹⁵ Top net solar radiation is the incoming solar radiation minus the outgoing solar radiation at the top of the atmosphere. It is the amount of radiation passing through a horizontal plane. This parameter is accumulated over a particular time. The units are joules per square meter (J m^{-2}).

¹⁶ We also try a robustness check that relies on the daily solar radiation calculated over the hours in the daytime. The effects of ozone pollution are almost unchanged. Results are available upon request.

we merge the variables of courier productivity, courier demographic characteristics, air pollution, and weather characteristics based on the city and date.

Table 2 presents the summary statistics of all the variables. We collect 66,374 observations of 1,511 couriers from 18 cities in 92 days. The average daily delivery volume of couriers is approximately 102 pieces. AQI has a mean of 61.9 and a maxima of 207. The maximum 8 h average ozone concentration has a mean of $101.5 \mu\text{g}/\text{m}^3$ and a maxima of $300 \mu\text{g}/\text{m}^3$. As a comparison, daily $\text{PM}_{2.5}$ (PM_{10}) has a mean of 27.2 (45.1) $\mu\text{g}/\text{m}^3$, and the average concentrations of the other air pollutants are remarkably low. Polluted days are most frequent in the central (and most developed) area of Guangdong Province, including Guangzhou, Foshan, Dongguan, and Zhongshan; less often in the surrounding four cities of Qingyuan, Jiangmen, Zhuhai, and Huizhou; and least frequent in the east and west areas of Guangdong province (Appendix Figure 4). The average daily maximum temperature is 32.6°C , and the average daily solar radiation is $25,270 \text{ kJ}/\text{m}^2$.

Among the 649 couriers with demographic characteristics, 99.4% are male, which is consistent with the high requirement of manual labour of this occupation. The average age of couriers is 29.2 years. On average, a courier has worked at T company for 1.6 years, but some couriers have worked at this company for more than 10 years. The number of education years has a mean of 10.9 and a maxima of 16, suggesting that an average courier receives education at the junior high school level. A dummy variable *Local* is defined as 1 if the *Hukou* of a courier is in Guangdong Province and 0 otherwise. A total of 43% of the couriers are local residents of Guangdong Province. Only a subset of the sample (26,920 observations) includes information of the hometown city, and 17% of couriers work in their hometown.

4. Empirical Models

We describe the empirical models to estimate the effects of ozone pollution

on the labour productivity of couriers.

4.1 Contemporaneous Effects of Ozone Pollution: OLS Estimation

Equation (1) estimates the contemporaneous effects of ozone pollution:

$$\log Y_{ict} = \alpha + \beta P_{ct} + \mathbf{W}_{ct}\boldsymbol{\gamma} + \delta_i + \eta_t + \varepsilon_{ict}, \quad (1)$$

where Y_{ict} refers to the delivery volume of courier i who works in city c on date t , and P_{ct} is the ozone pollution level of city c on date t . We consider two pollution measures: $Ozone_{ct}$, which refers to the maximum 8 h average concentration of ozone, and AQI_{ct} , which is the AQI for city c on date t .

We control for a rich set of weather characteristics in city c on date t (\mathbf{W}_{ct}), including daily maximum temperature, solar radiation, interactions of temperature bins and solar radiation, precipitation, maximum wind speed, average relative humidity, and atmospheric pressure. We divide the daily maximum temperature and precipitation amount into five bins, respectively, to allow for nonlinear effects of temperature and precipitation on courier productivity.¹⁷

We control for individual fixed effect δ_i , which absorbs time-invariant individual characteristics. The courier works in the same city across the sample period (three months). Thus, δ_i has already absorbed the city fixed effects, which control for city-level time-invariant characteristics including the market share of T company in different cities. Considering that the demand for express delivery services may fluctuate across seasons and differ between weekdays and weekends, we control for these common time trends by η_t , which includes the month fixed effects and day-of-week fixed effects. The identification is from the daily variation in ozone pollution within each courier

¹⁷ We observe only a few days with a maximum temperature lower than 30°C or higher than 36°C in the sample. Thus, we construct a group of dummy variables of daily maximum temperature, in which the j th dummy is equal to 1 if the maximum temperature falls into the j th bin of ($< 30^\circ\text{C}$ [the omitted group], $30^\circ\text{C}-32^\circ\text{C}$, $32^\circ\text{C}-34^\circ\text{C}$, $34^\circ\text{C}-36^\circ\text{C}$, $\geq 36^\circ\text{C}$). Similarly, according to China's classification criteria of precipitation intensity, we construct a group of dummy variables of daily precipitation amount, in which the j th dummy is equal to 1 if the precipitation amount falls into the j th bin of ($< 0.1\text{ mm}$ [no rain, the omitted group], $0.1-10\text{ mm}$ [light rain], $10-25\text{ mm}$ [moderate rain], $25-50\text{ mm}$ [heavy rain], $\geq 50\text{ mm}$ [super heavy rain]).

after controlling for weather characteristics, time-invariant location FE, common seasonal shocks, and weekend effects. Location/individual-by-time fixed effects are not controlled in the main model because a considerable amount of variation in ozone pollution may be absorbed due to the three-month time span of the sample. However, as robustness checks, we also try adding region by month FE or city by month FE in Equation (1). The estimated effect of ozone pollution is almost unchanged (Table 7). Finally, ε_{ict} is the error term. Standard errors are two-way clustered at the individual and date levels (Cameron et al. 2011), which allows for serial correlation within each courier and correlation across all couriers on the same day.¹⁸

As a robustness check, the individual fixed effects are replaced with individual characteristics \mathbf{X}_{it} and subsidiary fixed effects $Subsidiary_{kc}$:

$$\log Y_{ikct} = \alpha + \beta P_{ct} + \mathbf{W}_{ct}\boldsymbol{\gamma} + \mathbf{X}_{it}\boldsymbol{\theta} + Subsidiary_{kc} + \eta_t + \varepsilon_{ikct} \quad (2)$$

where k indexes subsidiary company k .

Increasing damages may be observed with the deterioration of air quality. We then explore the presence of nonlinear effects of ozone pollution on courier productivity using Equation (3):

$$\log Y_{ict} = \alpha + \sum_{j=1}^4 \beta_j P_{ctj} + \mathbf{W}_{ct}\boldsymbol{\gamma} + \delta_i + \eta_t + \varepsilon_{ict}, \quad (3)$$

where P_{ctj} is a series of dummy variables for different ozone pollution levels. We construct a group of dummy variables of AQI, in which the jth dummy is equal to 1 if AQI falls into the jth bin of $\{50-100, 100-150, 150-200, \text{ and } \geq 200\}$. AQI of 0–50, which represents excellent air quality according to the Ministry of Ecology and Environment of China, is used as the reference bin. Then β_j represents the loss of labour productivity when air quality does not reach the standard for excellent air quality. Similarly, we construct a group of dummy variables of ozone, in which the jth dummy is equal to 1 if ozone falls into the jth bin of $\{50-100, 100-150, 150-200, \geq 200\}$ to estimate the nonlinear effects of ozone.

¹⁸ We also try clustering the standard errors by city, and the main estimation results still hold. These results are available upon request.

4.2 Contemporaneous Effects of Ozone Pollution: IV Estimation

Measurement errors of the pollution levels associated with each courier may arise due to two reasons. First, the exact working area of each courier on each day is unknown.¹⁹ Second, the accurate air pollution level at each specific location is unidentified because pollution monitoring sites are sporadically distributed across the city. Thus, OLS may underestimate the negative effects of ozone pollution due to attenuation bias. In addition, omitted variables that correlate with ozone pollution and courier productivity may exist despite the rich fixed effects and control variables in Equations (1) to (3). Therefore, we use an IV approach to alleviate the potential bias from measurement errors and omitted variables.

Existing studies on the socioeconomic effects of air pollution that exploit meteorological phenomena for identification often rely on thermal inversion as an IV for air pollution (Arceo et al. 2016; Fu et al. 2018). Intuitively, air pollutants especially PM are trapped in the ground when the temperature at the surface falls below that above the surface. Thermal inversion phenomena rarely exist in Guangdong Province during the study period, thus rendering minimal variation to help identify the effects of ozone pollution.²⁰

We then construct the IVs for daily ozone pollution and AQI considering that air pollutants from the upwind nearby area can spread to the focal city via wind (Schlenker and Walker 2016; Barwick et al. 2019; Halliday et al. 2019; Heyes and Zhu 2019). A valid IV must satisfy the correlation and exogeneity conditions. First, numerous studies that rely on data in different countries show that long-range transport of ozone and its precursors may occur over several hundred kilometers (Brankov et al. 1998; Kato et al. 2004; Gao et al. 2016; Zhang et al. 2019). For example, recent modeling research of ozone

¹⁹ The exact working areas of each courier are trade secrets of the company and are unavailable for research.

²⁰ The frequency of thermal inversion in different cities of Guangdong Province in the study period is available upon request.

source apportionment shows that self-contribution to ozone in Guangzhou is only 13%–29%, and those of the other cities in Guangdong and nearby provinces are remarkable (Yang et al. 2019).²¹ The correlation condition of this IV is reassured through the strong first-stage estimates in the analyses (Table 5). As a robustness check, because NO₂ is a precursor of ozone, we also use the NO₂ in the upwind nearby cities to construct an IV for ozone in the focal city. The results remain largely unchanged (Appendix Table 5).

Second, changes in wind direction are natural phenomena and unaffected by human beings. Thus, pollution transmitted from the upwind nearby cities to the focal city can be considered an exogenous shock to the air pollution of the focal city and uncorrelated with the unobservables, such as the fluctuating intensity of economic activities in the focal city. We omit cities less than 50 km from the focal city when constructing the IV to alleviate the concern of endogeneity risk further (Heyes and Zhu 2019). The identification assumption is that ozone pollution in the nearby cities within a certain distance from the focal city can only influence courier productivity in the focal city through the effect on focal city ozone pollution. As a robustness check, we include nearby cities within 50 km and exclude those within 100 km from the focal city during the construction of IV (Appendix Table 6). The results remain largely unchanged. The imported pollution from nearby cities is also uncorrelated with the unobserved components of the measurement errors in workers' pollution exposure in the focal city. Thus, IV can alleviate the attenuation bias.

The specific procedures of constructing an IV for daily ozone pollution are as follows. First, we calculate the daily dominant wind direction for each city, namely, the average angle of wind direction weighted by wind speed and the associated number of lasting hours, from hourly data on wind direction and speed. For example, suppose wind direction is 30° at a wind speed of 3 m/s for 6 h and 45° at a wind speed of 4 m/s for the other 18 h, then the daily average angle of wind direction is $\frac{30^\circ \times 3 \times 6 + 45^\circ \times 4 \times 18}{3 \times 6 + 4 \times 18} = 42^\circ$. Second, we construct the

²¹ Guangzhou is the capital city of Guangdong Province.

weighted average of the pollution levels of all the upwind cities within 50–200 km from city c ($P_{source,ct}$) using Equation (4). Wind direction refers to the direction from which wind originates. Thus, ozone pollution in the upwind directions of city c may spread to this city via wind. In Equation (5), the weight on ozone pollution in nearby city j in the upwind direction of city c ($\omega_{j,t,c}$) is larger if the distance between city j and c (d_{jc}) is smaller and if the angle (θ_{jc}) between vector $\vec{j}\vec{c}$ and the daily dominant wind direction of city c is closer to zero as long as this angle is less than 90° (Figure 2).

$$P_{source,ct} = \sum_{\substack{j \text{ within } 50-200\text{km of } c \\ \cos\theta_{jc,t} > 0}} \omega_{j,t,c} \times P_{jt}, \quad (4)$$

$$\omega_{j,t,c} = \frac{\frac{\cos\theta_{jc,t}}{d_{jc}} \times 1(\cos\theta_{jc,t} > 0)}{\sum_{k \text{ within } 50-200\text{km of } c} \frac{\cos\theta_{kc,t}}{d_{kc}} \times 1(\cos\theta_{kc,t} > 0)}. \quad (5)$$

Third, considering that the transport of air pollutants takes time, we account for the influence of ozone pollution in the nearby cities in the preceding week. Thus, the IV for local ozone pollution P_{ct} can be written as

$$P_{IV,ct} = \sum_{s=t-7}^t \sum_{\substack{j \text{ within } 50-200\text{km of } c \\ \cos\theta_{jc,s} > 0}} \omega_{j,c,s} \times P_{js}. \quad (6)$$

The equation of the first stage of the two-stage least squared estimation (2SLS) can be written as follows:

$$P_{ct} = \alpha + \beta P_{IV,ct} + \mathbf{W}_{ct}\boldsymbol{\gamma} + \delta_i + \eta_t + \varepsilon_{ict}. \quad (7)$$

4.3 Cumulative Effects of Ozone Pollution on Labor Productivity

Air pollution may have cumulative effects on labour productivity (He et al. 2019). Moreover, the long-term health effects of ozone pollution remain largely unknown in the existing literature (US EPA 2020). Therefore, we use Equation (8) to estimate the cumulative effects of ozone pollution on courier productivity as a trial to address the gap in the literature.

$$\log Y_{ict} = \alpha + \sum_{k=0}^K \lambda_k P_{c,t-k} + \mathbf{W}_{ct}\boldsymbol{\gamma} + \delta_i + \eta_t + \varepsilon_{ict}, \quad (8)$$

where $P_{c,t-k}$ refers to the ozone pollution of city c on date $t - k$. K indexes a model with ozone pollution levels on current day (P_{ct}) and previous

K days ($\sum_{k=1}^K \lambda_k P_{c,t-k}$). After obtaining the estimated λ_k ($k = 0, 1, \dots, K$), the cumulative effect on courier productivity can be calculated if ozone pollution levels on the current day and previous K days all change by a certain unit.

A multicollinearity problem exists in the estimation of Equation (8) because air pollution is serially correlated across close days, and the problem becomes increasingly serious with additional lagged ozone pollution terms. Therefore, we use the polynomial distributed lag model [$PDL(K, N)$] to estimate the cumulative effects of ozone pollution (Schwartz 2000; Mar et al. 2005; He et al. 2019). K indexes the number of lagged daily ozone pollution terms that are added in the regression, and N refers to the highest polynomial degree. The PDL model requires that $N < K$. Under PDL, λ_k in Equation (8) can be expressed as follows:

$$\lambda_k = \sum_{n=0}^N \mu_n k^n = \mu_0 + \mu_1 k + \mu_2 k^2 + \dots + \mu_N k^N \quad (9)$$

For instance, when $N = 2$, substituting Equation (9) into (8) obtains the following equation:

$$\begin{aligned} \log Y_{ict} &= \alpha + \sum_{k=0}^K (\mu_0 + \mu_1 k + \mu_2 k^2) P_{c,t-k} + \mathbf{W}_{ct} \boldsymbol{\gamma} + \delta_i + \eta_t + \varepsilon_{ict} \\ &= \alpha + \sum_{k=0}^K (\mu_0 P_{c,t-k} + \mu_1 k P_{c,t-k} + \mu_2 k^2 P_{c,t-k}) + \mathbf{W}_{ct} \boldsymbol{\gamma} + \delta_i + \eta_t + \varepsilon_{ict} \\ &= \alpha + \mu_0 \sum_{k=0}^K P_{c,t-k} + \mu_1 \sum_{k=0}^K k P_{c,t-k} + \mu_2 \sum_{k=0}^K k^2 P_{c,t-k} \\ &\quad + \mathbf{W}_{ct} \boldsymbol{\gamma} + \delta_i + \eta_t + \varepsilon_{ict} \end{aligned} \quad (10)$$

The multicollinearity problem is largely mitigated in Equation (10) because the key independent variables ($P_{c,t-k}, k = 0, 1, \dots, K$) are transformed into different linear combinations of lagged ozone pollution terms. The cumulative effects of ozone pollution can be calculated after obtaining the results from the OLS or IV estimation.

5. Estimation Results

We first report the contemporaneous effects of ozone pollution (measured by maximum 8 h average concentration of ozone and AQI) on labour

productivity of couriers, including the OLS and the IV estimation results, and show that our results are robust across various robustness checks. We then provide evidence that ozone pollution does not influence labour supply and describe the heterogeneous effects of ozone pollution. We also demonstrate the cumulative effects of ozone pollution from the PDL model and compare the estimated contemporaneous and cumulative effects of ozone pollution with the existing literature. Finally, we calculate the ozone-pollution-induced income loss from decreased labour productivities for couriers in Guangdong and across China.

5.1 Effects of Ozone Pollution on Labor Productivity

5.1.1 OLS Estimation Results

We report the average effect of ozone on labour productivity in the top two panels of Table 3. In Panel A, log of the daily delivery volume of each courier is used as the dependent variable. Column (1) controls the individual FE, which has absorbed the subsidiary FE. Column (2) replaces the individual FE with the subsidiary FE, and adds the month and day-of-week FE. Column (3) includes individual and common time FE, as shown in Equation (1). Column (4) controls individual characteristics, subsidiary FE, and common time effects, as shown in Equation (2). The sample size in column (4) is smaller than that of the other columns because only 55% observations include individual characteristics.

Columns (1) and (2) show that a $10 \mu\text{g}/\text{m}^3$ increase in ozone significantly reduces the daily delivery volume of couriers by 0.72% and 0.32%, respectively. This finding implies the importance of controlling for common time effects to obtain correct estimates of the air pollution effects. In the preferred model in column (3), which controls individual heterogeneity and common time FE, a $10 \mu\text{g}/\text{m}^3$ increase in ozone significantly reduces the daily courier productivity by 0.35%. The standard deviation of ozone is $48.17 \mu\text{g}/\text{m}^3$, indicating that a one-standard-deviation increase in daily ozone pollution

decreases the daily labour productivity of couriers by 1.69%. In column (4), the estimated impact of -0.37% is also similar to that of column (3). We focus on the specification in column (3) for the interpretation of results and discussion in the following contents.

Panel B presents the results using daily courier productivity as the dependent variable. A 10 $\mu\text{g}/\text{m}^3$ increase in ozone significantly reduces daily delivery volume by 0.361 pieces of packages or 0.36% (of the sample average labour productivity of 101.57 pieces), which is highly similar to the results in Panel A. Overall, ozone has a robust significant negative effect on labour productivity.

We then report the average effects of AQI on daily courier productivity in Panels C and D of Table 3. A 10-unit increase in AQI significantly reduces the daily courier productivity by 0.38% (Panel C, logarithm of the individual productivity as the dependent variable) or 0.42% (Panel D). These numbers are consistent with the estimated 0.35%–0.36% reductions in labour productivity from a 10 $\mu\text{g}/\text{m}^3$ increase in ozone (Panels A and B of Table 3), which echoes that ozone is the dominant primary air pollutant in the sample.

5.1.2 Nonlinear Effects of Ozone Pollution on Labor Productivity

Revisions of the ambient air quality standards require scientific evidence on the lowest possible pollution level that may cause significant negative socioeconomic effects. Thus, we report the nonlinear effects of ozone pollution on courier productivity from Equation (3) in Table 4. Columns (1) and (2) present the nonlinear effects of ozone. Compared with the reference bin, labour productivity significantly decreases by 4.80% (column [1]) or 3.82% (column [2]) for ozone in the bin of 100–150 $\mu\text{g}/\text{m}^3$ and decreases by 4.03% (column [1]) or 4.02% (column [2]) in the bin of 150–200 $\mu\text{g}/\text{m}^3$. Once ozone exceeds 200 $\mu\text{g}/\text{m}^3$, average labour productivity decreases by 6.68% (column [1]) or 7.72% (column [2]). As a comparison, estimates from Equation (1) show that courier productivity decreases by 4.38%, 6.13%, and

7.88% (column [3], Panel A, Table 3) for ozone in the bins of 100–150 $\mu\text{g}/\text{m}^3$, 150–200 $\mu\text{g}/\text{m}^3$, and > 200 $\mu\text{g}/\text{m}^3$, respectively.²² Overall, models that examine the linear and nonlinear influences of ozone pollution yield highly similar estimated effects.

The ambient air quality standards of China indicate that the first- and second-class standards of the maximum allowable daily maximum 8 h average ozone concentration are 100 and 160 $\mu\text{g}/\text{m}^3$, respectively (Appendix Table 4). The results demonstrate that ozone can significantly reduce labour productivity and lead to low income of outdoor workers at levels even below the second-class standard.

Examining the nonlinear effects of AQI (columns [3] and [4]), we find that AQI starts to significantly decrease courier productivity after it exceeds 150. The coefficients on AQI that are in the ranges of 50–100 and 100–150 are relatively small. As explained in Section 2, ozone is the only contributor of AQI values that exceed 117. Thus, the significant nonlinear effects of AQI further confirm that the negative influences of ozone (instead of the other air pollutants) result in the estimated pollution effects on courier productivity.

5.1.3 Instrumental Variable Approach Estimation Results

The IV estimation results are reported in Table 5. Panel A presents the estimated effects of ozone. An IV for daily maximum 8 h average concentration of ozone of the focal city is constructed using those of the nearby cities, the geographic distance between the focal city and each nearby city, and the dominating wind direction of the focal city. The Kleibergen–Paap rk Wald F-statistics all surpass the threshold value of the Stock–Yogo weak IV test across different specification.²³ Moreover, the first-stage IV estimation shows that the constructed IV ($Ozone_{source}$) is significantly positively correlated with the ozone concentration of the focal city. These results

²² The 7.88% decrease in courier productivity when ozone exceeds 200 $\mu\text{g}/\text{m}^3$ is obtained from assuming ozone at 225 $\mu\text{g}/\text{m}^3$.

²³ The critical value of 10% level is 16.38 in our sample.

reassure the validity of the IV. Regarding the second-stage IV estimation results, columns (1) to (4) show that a 10 $\mu\text{g}/\text{m}^3$ increase in ozone significantly decreases labour productivity by 1.75%–2.56%, which are all significant at the 1% level. These effects are of substantially larger magnitudes than the OLS effects of 0.32%–0.72% decrease in labour productivity (Panel A, Table 3). Compared with the 1.69% estimated decrease from OLS, column (3) indicates that a one-standard-deviation increase in daily ozone pollution decreases the daily labour productivity of couriers by 8.91%.

Panel B of Table 5 presents the effects of AQI from IV estimation. Similarly, the Wald F-statistics all surpass the threshold of the weak IV test. In the second-stage IV estimation, a 10-unit increase in AQI decreases labour productivity by 2.15%–3.32%. Again, these effects are considerably larger than the OLS impacts of 0.34%–0.84% decrease in labour productivity (Panel C, Table 3). This finding further confirms the importance of using the IV to obtain accurate effects of ozone pollution. In addition, the estimated effects of ozone and AQI are consistent with each other. In the preferred specification (column (3)), the coefficient on ozone is slightly smaller than but is within one standard deviation of that on AQI.

5.2 Robustness Checks

Different studies have focused on the effects of different combinations of air pollutants based on the specific research question and data availability. As described above, ozone is the primary air pollutant for 80% of days in the sample (Table 1). However, people may still ponder on the influences of ozone pollution due to the existence of other air pollutants. We present the estimated effects of ozone when further controlling for the other air pollutants using different specifications in Table 6. Panels A and B present the OLS and IV estimation results, respectively. For each air pollutant, we construct an IV from the daily concentration of that air pollutant of the upwind nearby cities, wind direction of the focal city, and distance between each of the nearby and

focal cities. The IVs for all the included air pollutants are then utilized in each IV regression.

Ozone is mostly correlated with PM_{2.5} and PM₁₀ in the sample. Therefore, ozone and PM_{2.5} are controlled in column (1), and ozone and PM₁₀ are controlled in column (2). NO₂ is a precursor of ozone, and couriers, who frequently drive across the city, are likely susceptible to NO₂ because road traffic tends to be the largest source of NO₂ concentrations in Chinese cities. Therefore, ozone and NO₂ are controlled in column (3). Ozone, PM_{2.5}, and NO₂ are simultaneously controlled in column (4), and SO₂ and CO are further added in columns (5) and (6), respectively.²⁴ The OLS results show that a 10 µg/m³ increase in ozone significantly decreases labour productivity by 0.28%–0.36%, which is highly close to the 0.35% decrease obtained from the OLS regression that controls only ozone pollution (column [3], Panel A, Table 3). Coefficients on all the other air pollutants in Panel A are insignificant.

The IV regressions show that a 10 µg/m³ increase in ozone significantly decreases labour productivity by 1.93%–3.97%, which is slightly larger than the 1.85%–2.27% decrease obtained from the IV regression that controls only ozone pollution or AQI (column [3], Table 5). Other studies on the effects of air pollution have also found a similar pattern, that is, controlling for the other air pollutants may increase the magnitude of the coefficient of the core air pollutant. For instance, Heyes and Zhu (2019) find that the coefficient of PM_{2.5} on sleeplessness increases from 0.285 to 0.371 when NO₂ and ozone are further controlled and to 0.519 when ozone is added as a control. Schlenker and Walker (2016) find that the coefficient of CO is slightly larger when both CO and NO₂ are controlled. The robustness check results are consistent with the existing literature and imply that the estimated negative effects of ozone from the main model are unlikely to overestimate the real effects. None of the other air pollutants in Panel B has significant effects on courier productivity.

²⁴ The smaller particulates are more dangerous (Halliday et al. 2019), and the correlation coefficient between PM_{2.5} and PM₁₀ is as high as 0.965. Thus, we do not control for PM₁₀ in columns (4)–(6).

Appendix Table 7 presents several additional robustness checks of the IV regression results. First, the daily productivity records of couriers with less than 30 days of work records in the sample period are omitted from regression such that the truncated sample represents a group of couriers with relatively stable work records (columns [1] and [2]). Second, Typhoon “Nida” landed in Guangdong on the early morning of August 2, 2016, and its center moved out of Guangdong at 5:00 pm of the same day. Consequently, heavy rain occurred to many cities in Guangdong on August 2–3, 2016. Thus, we add a dummy variable, which represents the influence of Typhoon “Nida” in a city, to directly control the typhoon effects on labour productivity of the couriers (columns [3] and [4]).²⁵ The estimates in columns (1) to (4) remain significantly negative and are remarkably close to the main results.

Third, we add the level of ozone or AQI the next day as an additional explanatory variable and instrument for it using the pollution levels in the nearby cities and the focal city’s dominant wind direction the next day. Intuitively, future air pollution should not affect current labour productivity. Columns (5) and (6) of Appendix Table 7 show that ozone or AQI the next day does not affect current labour productivity significantly. The coefficients of current ozone (−2.24%) or AQI (−2.95%) are close to the ozone effect of −1.85% and the AQI effect of −2.27% (column [3], Table 5).

5.2.1 Exploring the Possible Effects of the Fluctuating Demand for Express Delivery

People may wonder whether demand for the express service is not high enough such that some couriers cannot deliver as many packages as they actually want. We already know from the company that the life of frontline couriers in China is highly fast-paced. We further examine the effects of ozone pollution and AQI on courier productivity in the highly urbanized area of

²⁵ Heavy rain occurred in Dongguan, Foshan, Guangzhou, Huizhou, Jiangmen, Shanwei, Shenzhen, Yunfu, Zhongshan, and Zhuhai on August 2, 2016 and in Guangzhou, Foshan, and Zhongshan on August 3, 2016.

Guangdong Province – the *PRD* region, which stimulates high demand for the express service, respectively.²⁶ Table 7 presents the estimation results from the subsample of the *PRD* region in column (1), Guangzhou and Shenzhen – the most developed cities in *PRD* – in column (2), and the *PRD* region, excluding Guangzhou and Shenzhen, in column (3).²⁷

In *PRD*, a 10 $\mu\text{g}/\text{m}^3$ increase in ozone significantly reduces labour productivity by 1.90%, which is close to the 1.85% estimated impact from the benchmark IV regression (column [3], Panel A, Table 5). Further decomposition of the *PRD* region shows that the estimates are only slightly different; the 1.83% productivity decrease in Guangzhou and Shenzhen (columns [2]) and the 2.25% decrease in the less developed cities in the *PRD* (columns [3]) are within one standard deviation of the 1.90% estimate using the *PRD* subsample. Exploring the effects of AQI in different areas also leads to a similar pattern of results.

In addition, people may wonder whether fluctuation in demand for express delivery services may influence the estimated pollution effects. First, we collect the exact dates of promotional activities of the top five electronic business platforms in China in 2016. The demand for express delivery can be remarkably higher than usual during some large promotional activities. For instance, “Double 11” is a day when many online stores offer huge discounts, and Chinese people go on massive Internet shopping. Appendix Table 8 shows that only one general promotional activity of *Suning.com*, which does not offer huge discounts to online shopping, falls in the study period. Second, we collect the daily Baidu search index of “express delivery” and “*T* express delivery company”, which are used as proxies for the search intensity of and demand for relevant express delivery services. Appendix Figure 5 shows that the fluctuation of the Baidu search index of the two terms is considerably

²⁶ Cities in the *PRD* region are Guangzhou, Foshan, Shenzhen, Dongguan, Huizhou, Zhongshan, Zhuhai, Jiangmen, and Zhaoqing.

²⁷ Guangzhou has 436 couriers, and Shenzhen has 559 couriers, thereby accounting for 65.9% of the data set.

small in the sample period. This corroborating evidence suggests that the current analysis is unlikely to be largely affected by demand shocks.

We further add location by month fixed effects in the main model to capture the possible effects of the fluctuating demand, and the results are presented in columns (4) – (7) of Table 7. In columns (4) – (5), we divide the sample into four regions, namely, the *PRD* Region, Eastern Guangdong, Northern Guangdong, and Western Guangdong, and add the region by month fixed effects. In columns (6) – (7), we add city by month fixed effects. Apparently, the coefficients of ozone and AQI are highly similar to those in the main model.

5.2.2 Placebo Test

As a placebo test, the air pollution level on date t is replaced with that on date $t - 60$. Theoretically, the pollution on date $t - 60$ should be uncorrelated with the air pollution on date t and have no influences on the labour productivity on date t . Table 8 presents the placebo test results. The coefficients on ozone pollution are all insignificant and of much smaller magnitude compared with those in Table 5. The “fake” pollution variables do not affect labour productivity, which further confirms that the main results are not driven by spurious variation in the data set.²⁸

5.3 Effect of Air Pollution on Labor Supply

In the long term, workers may migrate from cities with worse air quality to those with improved air quality. The present data set spans three months. Thus, assuming minimal sorting behavior based on ozone pollution in the study period is reasonable. People may wonder whether couriers may opt not to work under serious ozone pollution in the short term. On the one hand, T

²⁸ Another placebo test that replaces the air pollution level on date t with that on date $92 - t$ is also attempted, thus fully exploiting that the sample includes daily productivity records of 92 days. Air pollution variables are all insignificant and of small magnitudes across different models. The results are available upon request.

company has a strict fixed working schedule for all the couriers, which makes adjusting working days difficult for couriers. On the other hand, the income of the courier is generally low, which mostly comes from the volume of packages delivered. Thus, the possibility of deciding whether to work based on air quality is less for couriers. In addition, we define a dummy variable that represents courier labour supply, which is 1 if a courier has a work record on date t and 0 otherwise. We then estimate the effects of ozone pollution on the labour supply of couriers, and presents the results in Appendix Table 9. Columns (1) and (4) include the individual FE, while the other four columns also add the month and day-of-week FE. Columns (3) and (6) also include the concentration of ozone and value of AQI of the day before, respectively. All regressions control weather characteristics. Consistent with the existing literature (Graff Zivin and Neidell 2012; Chang et al. 2019), the effects of air pollution on the current day and the day before are insignificant and small in magnitude, thereby suggesting that ozone pollution does not significantly affect courier labour supply in the short term.

Although data on the exact working and non-working hours of each courier on each day are unavailable, discussion with the management team of T company shows that the working hours of the courier job are the same for every day. Couriers must travel to the express company to collect delivery materials and return to the company at the predetermined time. Thus, the working hour is not substantially different across days. If couriers opt to shift working hours within a day to avoid severe ozone pollution, the OLS estimates of the ozone pollution effect on courier productivity should be viewed as being inclusive of this adjustment. However, the IV estimation corrects the possible biases from the intra-day reallocation of working hours.

5.4 Heterogeneous Effects

We then explore the heterogeneous effects of air pollution across individual demographic characteristics and average labour productivity of couriers. We

explain the heterogeneous effects of ozone here and present the corresponding effects of AQI in Appendix Table 10-11.

5.4.1 Heterogeneous Effects of Ozone Across Demographic Characteristics

Based on the mean of each continuous demographic characteristic, we first define dummy variables for workers aged 30 years and above, who have worked at T company for over a year, and have an education level of high school and above. We then include each dummy variable and its interaction with the air pollution measure in Equation (1) to estimate the heterogeneous effects of ozone pollution. The gender difference in ozone pollution effects is not examined because 99.4% of the sample is for male couriers. Table 9 presents the results. Heterogeneous effects of ozone pollution are absent across age or education years (columns [1]–[2]). The homogenous effect of ozone across couriers with varying years of work is consistent with the finding in Graff Zivin and Neidell (2012), which reports the absence of heterogeneous effects of ozone across the tenure status of agricultural workers.

Column (4) includes an interaction between ozone and a dummy variable for holding a *Hukou* of Guangdong Province. *Hukou* is an indicator of being native. Results suggest that being native to Guangdong does not moderate the effect of ozone. In addition, column (5) shows that working in one's hometown can eliminate all the negative effects of ozone, suggesting the presence of long-term adaptation to ozone pollution. Intuitively, workers and managers may try to counteract the decrease in productivity from ozone pollution without knowing the reasons for decreased productivities, but the effectiveness of such actions may be the largest when one works in the most familiar environment, i.e., his/her hometown.

5.4.2 Heterogeneous Effects across Average Labor Productivity

The effect of ozone pollution on labour productivity may differ across workers with different productivities. We first calculate the average daily

labour productivity for each courier using records of his/her daily delivery volume across all days in the sample. Then, we divide all the couriers into three groups based on the tertiles of their average daily labour productivities and estimate the ozone pollution effect on labour productivity for each productivity group. Table 10 presents the results. Panels A and B present the estimation results on the daily labour productivity and its logarithm, respectively. Ozone pollution does not significantly influence courier labour productivity until the average daily delivery volume exceeds the lowest 33%. Furthermore, ozone pollution has a larger negative effect on couriers with higher average labour productivities. We find similar results from estimating the influence of AQI (Appendix Table 11). This result of the distributional effects of air pollution indicates that ozone pollution may lower the income inequality among outdoor workers.

5.5 Cumulative Effects of Air Pollution on Labor Productivity

Public health literature suggests that air pollution accumulated over the past 30 to 40 days may harm human health (Zanobetti et al. 2003). We examine the cumulative effects of ozone pollution on the labour productivity of couriers by estimating a polynomial distributed lag (PDL) model and incorporating the ozone pollution levels of the current and previous days as the explanatory variables. We estimate the quadratic ($PDL(K, 2)$) and the cubic ($PDL(K, 3)$) PDL models, and attempt individually the maximum number of previous days (K) from 5 to 35.

Figures 3 and 4 display the cumulative effects of ozone and AQI from incorporating the daily pollution levels of the 5 to 35 previous days in the regression, respectively. The vertical axis refers to the sum of the coefficients on the ozone pollution level or AQI of the current and all the previous days. The horizontal axis represents the number of previous days incorporated for analysis. Panels A and B display the results from the $PDL(K, 2)$ model, and Panels C and D display the results from the $PDL(K, 3)$ model.

Compared with the OLS estimates, the IV estimates are of larger magnitudes, which again confirms that OLS underestimates the productivity impacts of ozone pollution. Based on the IV estimates of the ozone pollution effect from the $PDL(K,3)$ model (Panel D, Figure 3), as the number of previous days incorporated (K) increases, the magnitude of the cumulative ozone pollution effect first slightly declines to around zero until K reaches approximately 10, increases until K reaches approximately 28, and then slightly decreases again. The IV estimates of the $PDL(K,2)$ model are qualitatively similar. Panels B and D of Figure 3 show that the cumulative ozone pollution effect becomes rather stable once the daily ozone pollution levels for the 30 previous days are incorporated for regressions.

Regarding the magnitude of the cumulative effect, Appendix Table 12 presents the cumulative effects of ozone pollution from incorporating the pollution level on each of the previous 5, 10, 15, 20, 25, 30, and 35 days. A $10 \mu\text{g}/\text{m}^3$ increase in ozone on each of the previous 30 days would significantly decrease labour productivity by 7.87%–8.18% (columns [2] and [4] of Appendix Table 12), indicating that a one-standard-deviation increase in daily ozone pollution over the previous 30 days can decrease labour productivity by 37.9%–39.4%. These results are significantly larger than the instantaneous productivity decrease due to a $10 \mu\text{g}/\text{m}^3$ increase in current day ozone pollution (column [3], Panel A, Table 5). Appendix Table 13 presents the cumulative effects of AQI on courier productivity, which renders similar estimates as the coefficients on ozone pollution. Thus, ignoring the cumulative effects of ozone pollution in the recent past days will underestimate the negative effect of ozone pollution in the short term.

5.6 Comparison with the Literature

We summarize the estimates of the contemporaneous and cumulative effects of air pollution on labour productivity in the existing literature in Table 11. Regarding the contemporaneous air pollution effects, Chang et al. (2016)

find that a $10 \mu\text{g}/\text{m}^3$ increase in $\text{PM}_{2.5}$ significantly decreases labour productivity by approximately 6% based on daily productivity data of indoor workers at a pear-packing factory in the US. Archsmith et al. (2018) find that a $1,000 \mu\text{g}/\text{m}^3$ ($1,145 \mu\text{g}/\text{m}^3$) increase in 12 h $\text{PM}_{2.5}$ (3 h CO) causes a 2.6% (11.5%) increase in the propensity of umpires to make incorrect calls. Using daily productivity data of indoor workers at two call centers in China, Chang et al. (2019) find that a 10 unit increase in the air pollution index (API) decreases daily productivity by 0.35%. Using daily productivity data of indoor workers at two factories of the textile industry in China, He et al. (2019) find that the contemporaneous effect of $\text{PM}_{2.5}$ is statistically insignificant. Using productivity data of assembly line workers in a ready-made garments firm in India, Adhvaryu et al. (2019) find that a $27 \mu\text{g}/\text{m}^3$ increase in fine PM decreases worker efficiency by half a point, which is 1.4% of the mean productivity.²⁹

This study finds that a $10 \mu\text{g}/\text{m}^3$ increase in ozone concentrations would significantly decrease labour productivity of outdoor couriers in China by 1.85% (column [3], Panel A, Table 5). This result is lower than the estimated effect of $\text{PM}_{2.5}$ in Chang et al. (2016) but is considerably larger than the other estimated influences of PM, CO, or API in the above literature. This discrepancy could be ascribed to the differences in the examined air pollutant, the working environment (outdoor or indoor), and the job skill. The main estimate in this paper is also considerably higher than the effect of ozone on the performance of track and field athletes in the US (Mullins 2018), but is close to the finding in Graff Zivin and Neidell (2012) that a $10 \mu\text{g}/\text{m}^3$ decrease in ozone concentrations increases the labour productivity of US agricultural harvest workers by 2.75%.

The finding regarding the insignificant coefficient on contemporaneous $\text{PM}_{2.5}$, which is consistent with He et al. (2019), may be attributed to the low

²⁹ There is a study whose finding is difficult to be compared with. Heyes et al. (2017) report that fine PM concentrations exceeding $15 \mu\text{g}/\text{m}^3$ cause a 2.3% reduction in the quality of parliament speech of Canadian members.

PM_{2.5} concentration in the sample. The 27.2 µg/m³ average concentration of PM_{2.5} is considerably lower than the 35 µg/m³ first-class limit of daily PM_{2.5} concentration in China's *Ambient Air Quality Standards* (GB 3095–2012) (Appendix Table 4).

Regarding cumulative and long-term effects of air pollution, He et al. (2019) find that a 10 µg/m³ increase in PM_{2.5} for the current and previous 25 days significantly decreases the labour productivity of indoor manufacturing workers by 0.5%–3%. Hansen (2018) discovers insignificant effects of PM on manufacturing productivity using the Annual Survey of Industries in India. Fu et al. (2018) report that a 1 µg/m³ increase in yearly average PM_{2.5} decreases manufacturing productivity by 0.82%. The present finding, in which a 10 µg/m³ increase in ozone on each of the previous 30 days significantly decreases labour productivity by 7.87%–8.18%, is consistent with Fu et al. (2018) but significantly larger than He et al. (2019) and Hansen-Lewis (2018). This comparison further corroborates that the respective properties of different air pollutants may result in different productivity/health effects such that extrapolating those found for one air pollutant to the others may be problematic.

5.7 Welfare Analysis

We calculate the income loss from the decreased labour productivities due to ozone pollution for couriers in Guangdong and across China. We abstract from the cumulative effects to simplify the calculation and focus on the contemporaneous effect of ozone. In the sample, a courier delivers 101 packages per day on average. The IV estimate indicates that a 10 µg/m³ increase in ozone leads to 1.85% fewer delivered packages by a courier.³⁰ The marginal income of delivering one package is typically 1 RMB (0.14 USD).

³⁰ The income loss is not calculated using the coefficient of AQI because AQI is a composite air quality index, which varies with the concentrations of not only ozone but also other air pollutants. The coefficient on AQI cannot simply be extrapolated to all year round because the estimates of the air pollution effect in this analysis are rooted in the influence of ozone (for instance, even for Guangdong Province, high AQI in winter is caused by high PM_{2.5} instead of ozone).

Table 4 suggests that the effect of ozone on labour productivity turns significantly negative once it exceeds 100 $\mu\text{g}/\text{m}^3$. The effect for ozone below 100 $\mu\text{g}/\text{m}^3$ is then ignored. Thus, when ozone concentration exceeds 100 $\mu\text{g}/\text{m}^3$, the average income loss of a courier due to a 1 $\mu\text{g}/\text{m}^3$ increase in ozone in 2016 can be calculated as follows:

$$LOSS_{ij} = \sum_{t=1}^{366} (Ozone_{jt} - 100) |_{Ozone_{jt} > 100} \times 0.185\% \times 101 \times 1. \quad (11)$$

Based on the daily air pollution data of all the 21 cities in Guangdong Province in 2016, we calculate the annual income loss from ozone pollution for an average courier, and the results are presented in Appendix Table 14. In Dongguan and Foshan, where air quality is among the worst, the annual income loss from ozone pollution exceeds 1,100 RMB for an average courier (157 USD).

We then calculate the potential annual income loss caused by ozone pollution for couriers in China. The State Post Bureau of China reports the delivery volume for each of the top 50 cities in the postal business, which together account for 83% of the total delivery volume in China in 2019. Combining the annual package delivery volume with the daily air pollution data at the city level in 2019, the annual income loss for couriers in each city can be calculated by the following equation:

$$LOSS_j = \sum_{t=1}^{365} (Ozone_{jt} - 100) |_{Ozone_{jt} > 100} \times 0.185\% \times Volume_j \times 1. \quad (12)$$

The ozone pollution induced income loss exceeding 270 million RMB (38.58 million USD) for couriers in the city of Guangzhou, while the total income loss in the top 50 cities of the express delivery business in China exceeds RMB 1.93 billion (USD 276.14 million) in 2019 (Appendix Table 15).

The income loss would be considerably higher if the cumulative effects of ozone pollution are further considered. Therefore, ozone pollution results in enormous welfare losses from declined labour productivity and reduced income of outdoor workers in China.

6. Conclusion

In this study, we merge high-frequency individual productivity data of couriers in Guangdong Province of China with daily air pollution variables to examine the contemporaneous and cumulative effects of ozone pollution on the labour productivity of outdoor workers. The notorious ozone pollution along with the low concentrations of other typical air pollutants in Guangdong during the summer allow for an advantageous context to estimate the productivity effect of ozone pollution. Our estimates show that a one-standard-deviation increase in daily daytime ozone pollution significantly decreases the courier productivity by 8.91%, whereas the same increase in ozone in the previous 30 days significantly decreases the courier productivity by 37.9%. Ozone pollution is likely to become more severe under more stagnant atmospheric conditions and increased atmospheric temperatures due to climate change (Zhang et al. 2019). Therefore, to increase labour productivity and mitigate the harmful effects on human health, our results warrant urgent calls for ozone pollution control policies in developing countries, where most of the attention is given to PM_{2.5} reductions.

The express delivery industry is becoming increasingly important in the post-COVID-19 era. Our conservative calculations show that ozone pollution induced more than 276.14 million USD in income loss for couriers in China's express industry in 2019. This finding implies that economic losses can be multiple times higher if the numerous linkages between the express industry and many other industries (e.g., e-commerce) and the productivity losses of similar outdoor workers are further considered.

The current calculation of welfare loss starts from ozone exceeding 100 $\mu\text{g}/\text{m}^3$ because our estimates suggest that ozone starts to influence labour productivity significantly once it exceeds 100 $\mu\text{g}/\text{m}^3$. However, negative health or productivity effects may still exist even if ozone concentration falls below 100 $\mu\text{g}/\text{m}^3$. As accumulating scientific evidence suggests that a threshold of ozone concentration below which the health risk is zero may not

exist (Zhang et al. 2019), exploring more data in developing countries to estimate the causal effects of ozone pollution at low levels seems a fruitful area for future research. In addition, although we find that ozone does not significantly influence the productivity of couriers who work in their hometowns, such adaptation in the long term may come hand in hand with increased health-care expenditures or administrative costs. Future research should explore the mechanisms of how different strategies/policies can effectively reduce the productivity damages caused by ozone.

Existing evidence suggests that environmental regulations that decrease emissions of NO_x and VOC, which are the precursors of ozone, may contribute to the reduction of ozone pollution (Deschenes et al. 2017; Li et al. 2020; Warneke et al. 2012). However, ozone pollution is expected to be a long-term problem. During the COVID-19 pandemic, researchers have found that ozone pollution increased and even breached standards in some cities after lockdown happened in areas such as China, Europe, and India (Almond et al. 2020; Awasthi 2020; Sicard et al. 2020), highlighting the challenge of reducing ozone even with strict measures controlling primary pollutant emissions. In developing countries, several known sources of ozone, including household use of consumer chemicals and biogenic emissions, are difficult to control through regulatory actions (Zhang et al. 2019). Therefore, future research should try to evaluate the effects of ozone pollution control policies to help with designing abatement policies of ozone. In addition, the complex formation mechanisms of PM_{2.5} and ozone suggest the existence of periods/regions with high concentrations of both pollutants. The optimal control of various air pollutants is beyond the scope of this study but needs insight from environmental scientists and economists.

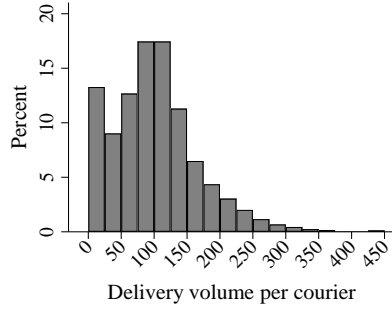
References

- Adhvaryu, Achyuta, Namrata Kala, and Anant Nyshadham. 2019. "Management and shocks to worker productivity." *National Bureau of Economic Research* (w25865).
- Almond, Douglas, Xinming Du, and Shuang Zhang. 2020. "Ambiguous Pollution Response to COVID-19 in China." *National Bureau of Economic Research* (w27086).
- Arceo, Eva, Rema Hanna, and Paulina Oliva. 2016. "Does the effect of pollution on infant mortality differ between developing and developed countries? Evidence from Mexico City." *The Economic Journal* 126(591): 257-280.
- Archsmith, James, Anthony Heyes, and Soodeh Saberian. 2018. "Air quality and error quantity: Pollution and performance in a high-skilled, quality-focused occupation." *Journal of the Association of Environmental and Resource Economists* 5(4): 827-863.
- Awasthi, Puja. 2020. "Ozone pollution increased during lockdown: Study." <https://www.theweek.in/news/sci-tech/2020/06/25/ozone-pollution-increased-during-lockdown-study.html>
- Bandiera, Oriana, Iwan Barankay, and Imran Rasul. 2005. "Social preferences and the response to incentives: Evidence from personnel data." *The Quarterly Journal of Economics* 120(3): 917-962.
- Barwick, Panle Jia, Shanjun Li, Deyu Rao, and Nahim Bin Zahur. 2018. "The morbidity cost of air pollution: evidence from consumer spending in China." *National Bureau of Economic Research* (w24688).
- Brankov, Elvira, S. Trivikrama Rao, and P. Steven Porter. 1998. "A trajectory-clustering-correlation methodology for examining the long-range transport of air pollutants." *Atmospheric Environment* 32(9): 1525-1534.
- Bloom, Nicholas, James Liang, John Roberts, and Zhichun Jenny Ying. 2015. "Does working from home work? Evidence from a Chinese experiment." *The Quarterly Journal of Economics* 130(1): 165-218.
- Cameron, A. Colin, Jonah B. Gelbach, and Douglas L. Miller. 2011. "Robust inference with multiway clustering." *Journal of Business & Economic Statistics* 29(2), 238-249.
- Center for Social Survey, Sun Yat-Sen University. "China Labor-force Dynamic Survey, 2016." <http://css.sysu.edu.cn/Data> (accessed September 2018).
- Chang, Tom Y., Joshua Graff Zivin, Tal Gross, and Matthew Neidell. 2019. "The effect of pollution on worker productivity: evidence from call center workers in China." *American Economic Journal: Applied Economics* 11(1): 151-72.
- Chang, Tom, Joshua Graff Zivin, Tal Gross, and Matthew Neidell. 2016. "Particulate pollution and the productivity of pear packers." *American Economic Journal: Economic Policy* 8(3): 141-69.
- China Center for Disease Control and Prevention. 2019. Health protection against ozone pollution cannot be ignored in summer, <https://rb.gy/eslynt>
- Cleary, Ekaterina Galkina, Manuel Cifuentes, Georges Grinstein, Doug Brugge, and Thomas B. Shea. 2018. "Association of low-level ozone with cognitive decline in older adults." *Journal of Alzheimer's Disease* 61(1): 67-78.
- Day, Drew B., Jianbang Xiang, Jinhan Mo, Feng Li, Mingkei Chung, Jicheng Gong, Charles J. Weschler et al. 2017. "Association of ozone exposure with cardiorespiratory pathophysiologic mechanisms in healthy adults." *JAMA Internal Medicine* 177(9): 1344-1353.
- Deschenes, Olivier, Michael Greenstone, and Joseph S. Shapiro. 2017. "Defensive investments and the demand for air quality: Evidence from the NOx budget

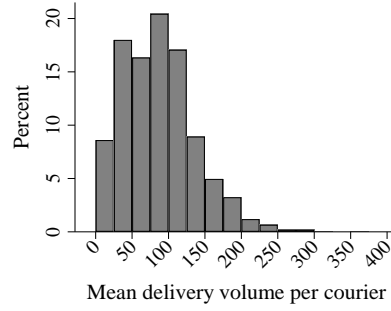
- program." *American Economic Review* 107(10): 2958-89.
- Dockery, Douglas W., and C. Arden Pope. 1994. "Acute respiratory effects of particulate air pollution." *Annual Review of Public Health* 15(1): 107-132.
- Fu, Shihe, V. Brian Viard, and Peng Zhang. 2018. "Air pollution and manufacturing firm productivity: Nationwide estimates for China." *Available at SSRN* (2956505).
- Gao, Jinhui, Bin Zhu, Hui Xiao, Hanqing Kang, Xuewei Hou, and Ping Shao. 2016. "A case study of surface ozone source apportionment during a high concentration episode, under frequent shifting wind conditions over the Yangtze River Delta, China." *Science of the Total Environment* 544: 853-863.
- Graff Zivin, Joshua, and Matthew Neidell. 2012. "The impact of pollution on worker productivity." *American Economic Review* 102(7): 3652-73.
- Halliday, Timothy J., John Lynham, and Áureo de Paula. 2019. "Vog: using volcanic eruptions to estimate the health costs of particulates." *The Economic Journal* 129(620): 1782-1816.
- Hansen-Lewis, Jamie. 2018. "Does Air Pollution Lower Productivity? Evidence from Manufacturing in India." *PAA 2018 Annual Meeting*.
- He, Jiaxiu, Haoming Liu, and Alberto Salvo. 2019. "Severe air pollution and labour productivity: Evidence from industrial towns in China." *American Economic Journal: Applied Economics* 11(1): 173-201.
- Health Effects Institute. 2019. "State of global air 2019."
- Heyes, Anthony, Nicholas Rivers, and Brandon Schaufele. 2019. "Pollution and politician productivity: the effect of pm on mps." *Land Economics* 95(2)157-173.
- Heyes, Anthony, and Mingying Zhu. 2019. "Air pollution as a cause of sleeplessness: Social media evidence from a panel of Chinese cities." *Journal of Environmental Economics and Management* 98: 102247.
- Huang, Jiekun, Nianhang Xu, and Honghai Yu. 2020. "Pollution and Performance: Do Investors Make Worse Trades on Hazy Days?." *Management Science*.
- Jayamurugan, Ramasamy, B. Kumaravel, S. Palanivelraja, and M. P. Chockalingam. 2013. "Influence of temperature, relative humidity and seasonal variability on ambient air quality in a coastal urban area." *International Journal of Atmospheric Sciences* 2013: 264046.
- Kahn, Matthew, and Pei Li. 2020. "Air pollution lowers high skill public sector worker productivity in China." *Environmental Research Letters*.
- Kato, Shungo, Yoshizumi Kajii, Ryunosuke Itokazu, Jun Hirokawa, Seiichiro Koda, and Yoshikatsu Kinjo. 2004. "Transport of atmospheric carbon monoxide, ozone, and hydrocarbons from Chinese coast to Okinawa island in the Western Pacific during winter." *Atmospheric Environment* 38(19): 2975-2981.
- Kim, Chong S., Neil E. Alexis, Ana G. Rappold, Howard Kehrl, Milan J. Hazucha, John C. Lay, Mike T. Schmitt et al. 2011. "Lung function and inflammatory responses in healthy young adults exposed to 0.06 ppm ozone for 6.6 hours." *American Journal of Respiratory and Critical Care Medicine* 183(9): 1215-1221.
- Lazear, Edward P. 2000. "Performance pay and productivity." *American Economic Review* 90(5): 1346-1361.
- Li, Ke, Daniel J. Jacob, Hong Liao, Lu Shen, Qiang Zhang, and Kelvin H. Bates. 2019. "Anthropogenic drivers of 2013–2017 trends in summer surface ozone in China." *Proceedings of the National Academy of Sciences* 116(2): 422-427.
- Li, Pei, Yi Lu, and Jin Wang. 2020. "The effects of fuel standards on air pollution: Evidence from China." *Journal of Development Economics* 146: 102488.

- Lippmann, Morton. 1989. "Health effects of ozone a critical review." *Japca* 39(5): 672-695.
- Mar, Therese F., Karen Jansen, Kristen Shepherd, Thomas Lumley, Timothy V. Larson, and Jane Q. Koenig. 2005. "Exhaled nitric oxide in children with asthma and short-term PM2.5 exposure in Seattle." *Environmental Health Perspectives* 113(12): 1791-1794.
- Mullins, Jamie T. 2018. "Ambient air pollution and human performance: Contemporaneous and acclimatization effects of ozone exposure on athletic performance." *Health Economics* 27(8): 1189-1200.
- Pilcher, June J., Eric Nadler, and Caroline Busch. 2002. "Effects of hot and cold temperature exposure on performance: a meta-analytic review." *Ergonomics* 45(10): 682-698.
- Schlenker, Wolfram, and W. Reed Walker. 2016. "Airports, air pollution, and contemporaneous health." *The Review of Economic Studies* 83(2): 768-809.
- Schwartz, Joel. 2000. "The distributed lag between air pollution and daily deaths." *Epidemiology* 11(3): 320-326.
- Sicard, Pierre, Alessandra De Marco, Evgenios Agathokleous, Zhaozhong Feng, Xiaobin Xu, Elena Paoletti, José Jaime Diéguez Rodríguez, and Vicent Calatayud. 2020. "Amplified ozone pollution in cities during the COVID-19 lockdown." *Science of The Total Environment*: 139542.
- Somanathan, Eswaran, Rohini Somanathan, Anant Sudarshan, and Meenu Tewari. 2018. "The impact of temperature on productivity and labour supply: Evidence from Indian manufacturing." *BFI Working Paper* No. 2018-69.
- State Post Bureau of China. 2016. Report of the operation of the postal industry in 2016. http://www.spb.gov.cn/xw/dtxx_15079/201701/t20170114_959038.html
- State Post Bureau of China. 2019. Report of the operation of the postal industry in 2019. http://www.spb.gov.cn/xw/dtxx_15079/202001/t20200114_2005598.html
- U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Health and Environmental Impacts Division. 2020. Policy Assessment for the Review of the Ozone National Ambient Air Quality Standards (NAAQS), EPA-452/R-20-001.
- Warneke, Carsten, Joost A. De Gouw, John S. Holloway, Jeff Peischl, Thomas B. Ryerson, Elliot Atlas, Don Blake, Michael Trainer, and David D. Parrish. 2012. "Multiyear trends in volatile organic compounds in Los Angeles, California: Five decades of decreasing emissions." *Journal of Geophysical Research: Atmospheres* 117(D00V17).
- Yang, Wenyi, Huansheng Chen, Wending Wang, Jianbin Wu, Jie Li, Zifa Wang, Junyu Zheng, and Duohong Chen. 2019. "Modeling study of ozone source apportionment over the Pearl River Delta in 2015." *Environmental Pollution* 253: 393-402.
- Zanobetti, Antonella, Joel Schwartz, Evi Samoli, Alexandros Gryparis, Giota Touloumi, Janet Peacock, Ross H. Anderson et al. 2003. "The temporal pattern of respiratory and heart disease mortality in response to air pollution." *Environmental Health Perspectives* 111(9): 1188-1193.
- Zhang, Junfeng, Yongjie Wei, and ZhangFu Fang. 2019. "Ozone pollution: A major health hazard worldwide." *Frontiers in Immunology* 10: 2518.

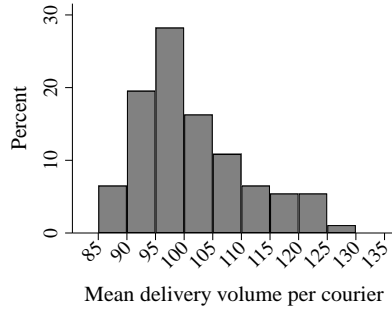
Panel A. Across workers and days



Panel B. Across workers



Panel C. Across days



Panel D. Over days

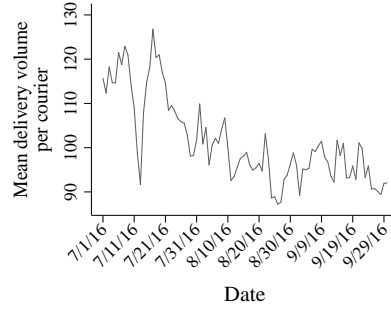


Figure 1: Distribution of labour productivity

Source: *T* express company Guangdong office. Panel A: Distribution of the daily delivery volume across couriers over different days. Panel B: Distribution of the average labour productivity over the sample period across different couriers. Panel C: Distribution of the average daily delivery volume per courier over different days. Panel D: Average delivery volume per courier on each day.

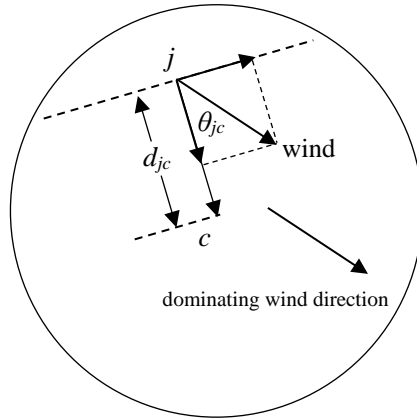


Figure 2: Illustration of wind direction and the transport of ozone pollution from city j to city c .

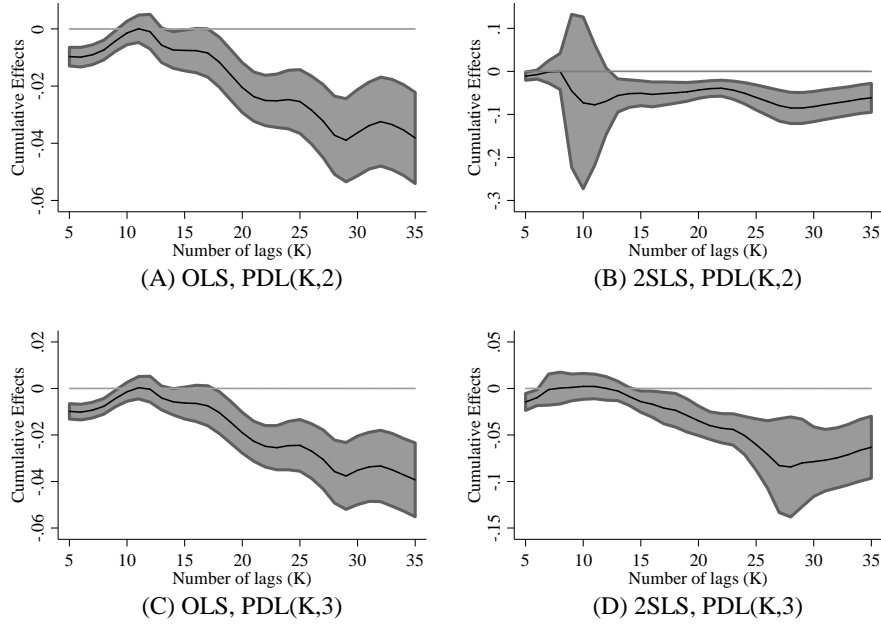


Figure 3: Cumulative effects of ozone on courier productivity.

Notes: Panels (A) to (B) present the results from PDL (K,2) + OLS, PDL (K,2) + 2SLS, PDL (K,3) + OLS, and PDL (K,3) + 2SLS, respectively. Each panel presents the cumulative air pollution effects from incorporating the daily ozone concentrations of the previous 5 to 35 days individually. The vertical axis represents the sum of coefficients on ozone/10. Each dot on the solid line represents the corresponding $\sum_{k=0}^K \lambda_k$, where K is the number of preceding days incorporated ($K \in [5, 35]$), while the shaded area represents the 95% confidence intervals. All regressions control daily maximum temperature dummies, sun radiation, maximum temperature dummies \times sun radiation, precipitation, maximum wind speed, atmospheric pressure, relative humidity, individual FE, month FE, and day-of-week FE. The shape of the curve in Panel (B) appears different from that in Panel (D), but the range of the estimates in Panel (B) is close to that in Panel (D) (columns [2] and [4] of Appendix Table 12).

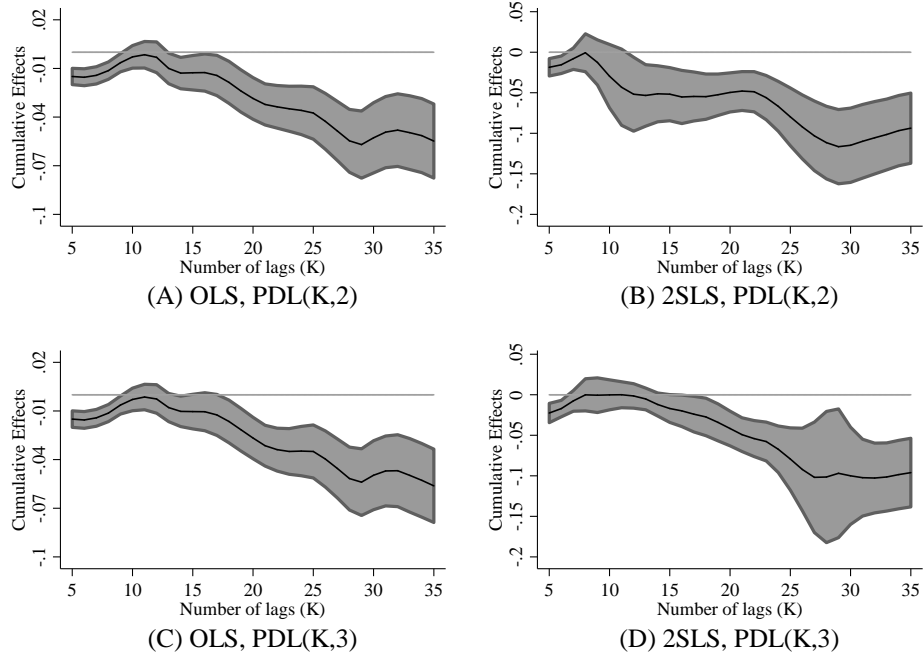


Figure 4: Cumulative effects of AQI on courier productivity.

Note: Panels (A) to (B) present the results from PDL (K,2) + OLS, PDL (K,2) + 2SLS, PDL (K,3) + OLS, and PDL (K,3) + 2SLS, respectively. Each panel presents the cumulative air pollution effects from incorporating the daily values of AQI of the previous 5 to 35 days. The vertical axis represents the sum of coefficients on AQI/10. Each dot on the solid line represents the corresponding $\sum_{k=0}^K \lambda_k$, where K is the number of preceding days incorporated ($K \in [5, 35]$), while the shaded area represents the 95% confidence intervals. All regressions control daily maximum temperature dummies, sun radiation, maximum temperature dummies \times sun radiation, precipitation, maximum wind speed, atmospheric pressure, humidity, individual FE, month FE, and day-of-week FE.

Table 1: Percentage of days that each primary air pollutant is accountable for in Guangdong province of China

| Primary air pollutant | % of days in 2016 | % of days during July 1 – September 30, 2016 |
|-------------------------|-------------------|--|
| Ozone (O ₃) | 42.69 | 79.63 |
| PM _{2.5} | 31.58 | 8.80 |
| NO ₂ | 13.36 | 3.79 |
| PM ₁₀ | 14.69 | 9.01 |
| CO | 0.30 | 0.00 |
| SO ₂ | 0.05 | 0.00 |

Notes: The National Environmental Monitoring Center (NEMC) of China provides information of the primary air pollutant in each city on each day. The percentages add up to over 100% because there can be more than one primary air pollutant in one day. The percentages are calculated by dividing the number of days that the primary air pollutant is accountable for by the number of days with AQI over 50.

Table 2: Summary statistics

| Variable | Mean | SD | Max | Min |
|---|--------|-------|--------|-------|
| <i>Labor productivity (66374 obs.)</i> | | | | |
| volume of delivery | 101.57 | 65.85 | 430 | 5 |
| <i>Air pollution variables</i> | | | | |
| AQI | 61.88 | 33.57 | 207 | 20 |
| Ozone (daily max. 8-hr avg.) (μg/m ³) | 101.46 | 48.17 | 300 | 18 |
| NO ₂ (μg/m ³) | 23.01 | 10.75 | 67 | 4 |
| PM _{2.5} (μg/m ³) | 27.20 | 14.43 | 88 | 6 |
| PM ₁₀ (μg/m ³) | 45.06 | 19.47 | 125 | 12 |
| SO ₂ (μg/m ³) | 11.82 | 4.99 | 46 | 2 |
| CO (mg/m ³) | 0.81 | 0.19 | 1.7 | 0.4 |
| <i>Weather characteristics</i> | | | | |
| max. temperature (°C) | 32.64 | 2.48 | 38.9 | 19.7 |
| precipitation (mm) | 8.44 | 18.43 | 168.8 | 0.0 |
| max. wind speed (m/s) | 4.21 | 1.63 | 18.5 | 1.6 |
| wind direction (°) | 170.39 | 63.97 | 345.8 | 21.3 |
| atmospheric pressure (hPa) | 998.58 | 5.32 | 1014.7 | 981.7 |
| avg. relative humidity (%) | 82.01 | 8.73 | 100.0 | 55.0 |
| avg. solar radiation (10 ³ kJ/m ²) | 25.27 | 4.67 | 33.7 | 10.7 |
| <i>Demographic characteristics (36496 obs.)</i> | | | | |
| male (0/1) | 0.99 | 0.08 | 1 | 0 |
| age | 29.22 | 6.14 | 54 | 17 |
| years of working | 1.55 | 1.33 | 16 | 1 |
| Hukou in Guangdong or not (0/1) | 0.43 | 0.50 | 1 | 0 |
| Work in hometown or not (0/1), 26920 obs. | 0.17 | 0.38 | 1 | 0 |
| years of education | 10.87 | 1.82 | 16 | 6 |

Notes: For wind direction, 0 means the wind blows from the due north to the south, and 180 means the wind blows from the due south to the north.

Table 3: Effects of ozone and AQI on labour productivity (OLS)

| | (1) | (2) | (3) | (4) |
|---|-------------------------|-----------------------|------------------------|-----------------------|
| | Preferred specification | | | |
| Panel A: | | | | |
| Dependent variable: Log (Delivery Volume) | | | | |
| Ozone/10 | -0.0072*** (0.0017) | -0.0032** (0.0014) | -0.0035** (0.0014) | -0.0037** (0.0015) |
| R-squared | 0.495 | 0.172 | 0.497 | 0.191 |
| Panel B: | | | | |
| Dependent variable: Delivery Volume | | | | |
| Ozone/10 | -0.7157*** (0.1627) | -0.3311** (0.1322) | -0.3612*** (0.1357) | -0.3853** (0.1505) |
| R-squared | 0.554 | 0.188 | 0.559 | 0.222 |
| Panel C: | | | | |
| Dependent variable: Log (Delivery Volume) | | | | |
| AQI/10 | -0.0084*** (0.0023) | -0.0034* (0.0018) | -0.0038** (0.0018) | -0.0047** (0.0019) |
| R-squared | 0.494 | 0.171 | 0.497 | 0.191 |
| Panel D: | | | | |
| Dependent variable: Delivery Volume | | | | |
| AQI/10 | -0.8618*** (0.2176) | -0.3836** (0.1718) | -0.4299** (0.1725) | -0.4723** (0.1926) |
| R-squared | 0.554 | 0.188 | 0.558 | 0.222 |
| Individual FE | Yes | No | Yes | No |
| Month FE | No | Yes | Yes | Yes |
| Day-of-week FE | No | Yes | Yes | Yes |
| Subsidiary FE | No | Yes | No | Yes |
| Individual characteristics | No | No | No | Yes |
| Observations | 66374 | 66374 | 66374 | 36496 |

Notes: Each cell represents the coefficient from a separate regression that estimates the effect of either ozone or AQI on courier productivity. The sample consists of worker–day observations. Standard errors two-way clustered by worker and date are reported in parentheses. All regressions control dummy variables of daily maximum temperature, solar radiation, dummy variables of maximum temperature \times solar radiation, precipitation, maximum wind speed, atmospheric pressure, and relative humidity at the daily level.

Table 4: Nonlinear effects of ozone and AQI on labour productivity

| | (1) | (2) | (3) | (4) |
|----------------------------|-----------------------|------------------------|-----------------------|-------------------------|
| Dependent variable | Log (Delivery Volume) | Delivery Volume | Log (Delivery Volume) | Delivery Volume |
| Air pollution variable | Ozone | Ozone | AQI | AQI |
| <i>Air pollution bins:</i> | | | | |
| 50–100 | -0.0174 (0.0175) | -1.4971 (1.4920) | -0.0151 (0.0122) | -1.5616 (1.0612) |
| 100–150 | -0.0480** (0.0210) | -3.8756* (1.9730) | -0.0127 (0.0212) | -1.7838 (1.9472) |
| 150–200 | -0.0403 (0.0253) | -4.0838* (2.3701) | -0.0377 (0.0277) | -5.1169** (2.3113) |
| >200 | -0.0668** (0.0270) | -7.8456*** (2.4899) | -0.0687** (0.0264) | -10.0842*** (2.5379) |
| Individual FE | Yes | Yes | Yes | Yes |
| Month FE | Yes | Yes | Yes | Yes |
| Day-of-week FE | Yes | Yes | Yes | Yes |
| R-squared | 0.497 | 0.559 | 0.497 | 0.558 |
| Observations | 66374 | 66374 | 66374 | 66374 |

Notes: The unit of the ozone variable is $\mu\text{g}/\text{m}^3$. Each column represents the coefficients from a separate regression that estimates the effect of either ozone or AQI on courier productivity. The sample consists of worker–day observations. Standard errors two-way clustered by worker and date are reported in parentheses. All regressions control dummy variables of daily maximum temperature, solar radiation, dummy variables of maximum temperature \times solar radiation, precipitation, maximum wind speed, atmospheric pressure, and relative humidity at the daily level.

Table 5: Effects of ozone and AQI on labour productivity (2SLS)

| | (1) | (2) | (3) | (4) |
|-----------------------------|--|------------------------|------------------------|------------------------|
| | Preferred specification | | | |
| Panel A: effects of ozone | | | | |
| | Second Stage (Dependent variable: Log (delivery volume)) | | | |
| Ozone/10 | -0.0256*** (0.0050) | -0.0185*** (0.0047) | -0.0185*** (0.0046) | -0.0175*** (0.0050) |
| | First Stage (Dependent variable: Ozone/10) | | | |
| Ozone _{source} /10 | 0.6539*** (0.0935) | 0.5934*** (0.1001) | 0.5944*** (0.0987) | 0.6304*** (0.1013) |
| Wald F statistic | 48.954 | 35.161 | 36.262 | 38.761 |
| Panel B: effects of AQI | | | | |
| | Second Stage (Dependent variable: Log (delivery volume)) | | | |
| AQI/10 | -0.0332*** (0.0068) | -0.0228*** (0.0063) | -0.0227*** (0.0061) | -0.0215*** (0.0066) |
| | First Stage (Dependent variable: AQI/10) | | | |
| AQI _{source} /10 | 0.6870*** (0.1048) | 0.6554*** (0.1133) | 0.6563*** (0.1119) | 0.6848*** (0.1137) |
| Wald F statistic | 42.927 | 33.459 | 34.386 | 36.281 |
| Individual FE | Yes | No | Yes | No |
| Month FE | No | Yes | Yes | Yes |
| Day-of-week FE | No | Yes | Yes | Yes |
| Subsidiary FE | No | Yes | No | Yes |
| Individual Characteristics | No | No | No | Yes |
| Observations | 66374 | 66374 | 66374 | 36496 |

Notes: The sample consists of worker–day observations. Standard errors two-way clustered by worker and date are reported in parentheses. All regressions control dummy variables of daily maximum temperature, solar radiation, dummy variables of maximum temperature \times solar radiation, precipitation, maximum wind speed, atmospheric pressure, and relative humidity at the daily level. Wald F statistic refers to the Kleibergen–Paap rk Wald F statistic, which is used to check whether there is a weak IV or not.

Table 6: Effects of ozone when controlling for other air pollutants

| | (1) | (2) | (3) | (4) | (5) | (6) |
|---------------------------------|------------------------|------------------------|------------------------|------------------------|-----------------------|------------------------|
| Panel A: OLS estimation | | | | | | |
| Ozone/10 | -0.0035* (0.0018) | -0.0036** (0.0018) | -0.0028* (0.0016) | -0.0035* (0.0018) | -0.0035* (0.0018) | -0.0034* (0.0019) |
| PM _{2.5} /10 | 0.0001 (0.0063) | | | 0.0051 (0.0076) | 0.0057 (0.0080) | 0.0028 (0.0084) |
| PM ₁₀ /10 | | 0.0006 (0.0047) | | | | |
| NO ₂ /10 | | | -0.0065 (0.0088) | -0.0101 (0.0106) | -0.0091 (0.0110) | -0.0112 (0.0109) |
| SO ₂ /10 | | | | | -0.0080 (0.0243) | |
| CO | | | | | | 0.0341 (0.0516) |
| Panel B: 2SLS estimation | | | | | | |
| Ozone/10 | -0.0306*** (0.0097) | -0.0352*** (0.0111) | -0.0193*** (0.0068) | -0.0296*** (0.0094) | -0.0397** (0.0199) | -0.0338*** (0.0102) |
| PM _{2.5} /10 | 0.0312 (0.0242) | | | 0.0376 (0.0279) | 0.0120 (0.0621) | 0.1142 (0.1394) |
| PM ₁₀ /10 | | 0.0331 (0.0218) | | | | |
| NO ₂ /10 | | | 0.0038 (0.0248) | -0.0182 (0.0322) | -0.0637 (0.1023) | 0.0037 (0.0510) |
| SO ₂ /10 | | | | | 0.5599 (1.0436) | |
| CO | | | | | | -0.8658 (1.6677) |
| Individual FE | Yes | Yes | Yes | Yes | Yes | Yes |
| Month FE | Yes | Yes | Yes | Yes | Yes | Yes |
| Day-of-week FE | Yes | Yes | Yes | Yes | Yes | Yes |
| Observations | 66374 | 66374 | 66374 | 66374 | 66374 | 66374 |

Notes: The sample consists of worker–day observations. Standard errors two-way clustered by worker and date are reported in parentheses. All regressions control dummy variables of daily maximum temperature, solar radiation, dummy variables of maximum temperature \times solar radiation, precipitation, maximum wind speed, atmospheric pressure, and relative humidity at the daily level.

Table 7: Robustness checks from examining the effects of the fluctuating demand

| | (1) | (2) | (3) | (4) | (5) | (6) | (7) |
|------------------------------------|-----------------------------|-------------------------------------|----------------------------|------------------------|------------------------|------------------------|------------------------|
| | Subsample analyses | | | | | | |
| | Pearl River Delta Region | Guangzhou (GZ) and Shenzhen (SZ) | PRD excluding GZ and SZ | | | | |
| Ozone/10 | -0.0190*** (0.0050) | -0.0183*** (0.0059) | -0.0225*** (0.0054) | -0.0177*** (0.0045) | | -0.0176*** (0.0045) | |
| AQI/10 | -0.0226*** (0.0064) | -0.0214*** (0.0074) | -0.0263*** (0.0068) | | -0.0216*** (0.0060) | | -0.0215*** (0.0060) |
| Individual FE | Yes | Yes | Yes | | | | |
| Month FE | Yes | Yes | Yes | | | | |
| Day-of-week FE | Yes | Yes | Yes | | | | |
| Average daily delivering volume | 105.85 | 106.22 | 104.20 | | | | |
| Average AQI | 66.84 | 66.52 | 68.26 | | | | |
| Additional fixed effects | | | | region × month | | city × month | |
| Observations | 57028 | 46501 | 10527 | 66374 | 66374 | 66374 | 66374 |

Notes: Each cell represents the coefficient from a separate regression that estimates the effect of either ozone or AQI on courier productivity. The sample consists of worker–day observations. All regressions are estimated by 2SLS. Regions include the Pearl River Delta Region, Eastern Guangdong, Northern Guangdong, and Western Guangdong. Standard errors two-way clustered by worker and date are reported in parentheses. All regressions control dummy variables of daily maximum temperature, solar radiation, dummy variables of maximum temperature × solar radiation, precipitation, maximum wind speed, atmospheric pressure, and relative humidity at the daily level.

Table 8: Placebo test of the air pollution effects on labour productivity

| | (1) | (2) | (3) | (4) |
|--|---------------------|---------------------|---------------------|---------------------|
| Ozone/10 | -0.0010 (0.0042) | -0.0032 (0.0047) | | |
| AQI/10 | | | -0.0003 (0.0062) | -0.0048 (0.0071) |
| Individual FE | Yes | No | Yes | No |
| Month FE | Yes | Yes | Yes | Yes |
| Day-of-week FE | Yes | Yes | Yes | Yes |
| Subsidiary FE | No | Yes | No | Yes |
| Individual characteristics | No | Yes | No | Yes |
| Wald F statistic of first stage estimation | 24.061 | 24.061 | 26.311 | 24.376 |
| Observations | 66374 | 36496 | 66374 | 36496 |

Notes: The sample consists of worker–day observations. Standard errors two-way clustered by worker and date are reported in parentheses. All regressions control dummy variables of daily maximum temperature, solar radiation, dummy variables of maximum temperature \times solar radiation, precipitation, maximum wind speed, atmospheric pressure, and relative humidity at the daily level. All regressions are estimated by 2SLS.

Table 9: Heterogeneous effects of ozone on labour productivity

| | (1) | (2) | (3) | (4) | (5) |
|---|--------------------------------|------------------------|------------------------|------------------------|------------------------|
| Ozone | -0.0167*** (0.0054) | -0.0153*** (0.0057) | -0.0156*** (0.0053) | -0.0208*** (0.0059) | -0.0210*** (0.0060) |
| Ozone \times 30 years old or above | -0.0050 (0.0048) | | | | |
| Ozone \times High school or above | | -0.0006 (0.0006) | | | |
| Ozone \times career duration longer than 1 year | | | -0.0086 (0.0053) | | |
| Ozone \times <i>Hukou</i> in Guangdong | | | | 0.0064 (0.0048) | |
| Ozone \times Work in the hometown | | | | | 0.0210** (0.0092) |
| Fixed effects | individual, month, day-of-week | | | | |
| Observations | 36496 | 36496 | 36496 | 36496 | 26920 |

Notes: The sample consists of worker–day observations. All regressions are estimated by 2SLS. Standard errors two-way clustered by worker and date are reported in parentheses. All regressions control dummy variables of daily maximum temperature, solar radiation, dummy variables of maximum temperature \times solar radiation, precipitation, maximum wind speed, atmospheric pressure, and relative humidity at the daily level.

Table 10: Effects of ozone on labour productivity across couriers with different average productivities

| | (1) | (2) | (3) |
|---|---------------------|------------------------|------------------------|
| Average daily delivery volume | Lowest 33% | 33%-67% | Top 33% |
| Panel A: Dependent variable: Delivery Volume | | | |
| Ozone/10 | -0.2140 (0.2567) | -1.2325*** (0.3722) | -2.1840*** (0.5165) |
| Panel B: Dependent variable: Log (Delivery Volume) | | | |
| Ozone/10 | 0.0005 (0.0065) | -0.0211*** (0.0062) | -0.0223*** (0.0054) |
| Individual FE | Yes | Yes | Yes |
| Month FE | Yes | Yes | Yes |
| Day-of-week FE | Yes | Yes | Yes |
| Observations | 12685 | 25042 | 28647 |

Notes: Each cell represents the coefficient from a separate regression that estimates the effect of ozone on courier productivity. The sample consists of worker–day observations. Dependent variable is the daily delivery volume of each courier. All regressions are estimated by 2SLS. Standard errors two-way clustered by worker and date are reported in parentheses. All regressions control dummy variables of daily maximum temperature, solar radiation, dummy variables of maximum temperature \times solar radiation, precipitation, maximum wind speed, atmospheric pressure, and relative humidity at the daily level.

Table 11: Summary of the estimated air pollution impacts on labour productivity in the literature

| Paper | Country | Type of work | Pollutant | Increase in pollutant concentration | Decrease in labour productivity |
|---|---------|--|-------------------|--|---------------------------------|
| Panel A: contemporaneous effects of air pollution | | | | | |
| this study | China | couriers | ozone | 10 $\mu\text{g}/\text{m}^3$ | 1.85% |
| Graff Zivin and Neidell (2012) | US | agricultural harvest workers | ozone | 10 $\mu\text{g}/\text{m}^3$ (5 ppb) | 2.81% |
| Chang et al. (2016) | US | pear packers (indoor) | PM _{2.5} | 10 $\mu\text{g}/\text{m}^3$ | 6% |
| Mullins (2017) | US | track and field athletes | ozone | 10 $\mu\text{g}/\text{m}^3$ | 0.20% |
| Archsmith et al. (2018) | US | baseball umpires | PM _{2.5} | 1000 $\mu\text{g}/\text{m}^3$ (10 mg/m ³) | 2.60% |
| | | | CO | 1145 $\mu\text{g}/\text{m}^3$ (1 ppm) | 11.50% |
| Chang et al. (2019) | China | call center workers (indoor) | API | 10 units | 0.35% |
| He et al. (2019) | China | workers in textile industry (indoor) | PM _{2.5} | -- | insignificant |
| Heyes et al. (2019) | Canada | members of parliament (indoor) | PM _{2.5} | >15 $\mu\text{g}/\text{m}^3$ | 2.30% |
| Adhvaryu et al. (2019) | India | assembly line workers in a ready-made garments firm (indoor) | fine PM | 27 $\mu\text{g}/\text{m}^3$ | 1.40% |
| Panel B: cumulative/long-term effects of air pollution | | | | | |
| this study | China | couriers | ozone | 10 $\mu\text{g}/\text{m}^3$ for the current and previous 30 days | [7.9%, 8.2%] |
| Fu et al. (2018) | China | Industrial Enterprise Database | PM ₁₀ | 1 $\mu\text{g}/\text{m}^3$ in yearly average | 0.82% |
| Hansen (2018) | India | Annual Survey of Industries | AOD (PM) | -- | insignificant |
| He et al. (2019) | China | workers in textile industry (indoor) | PM _{2.5} | 10 $\mu\text{g}/\text{m}^3$ for the current and previous 25 days | [0.5%, 3%] |

Online Appendix of “Productivity Loss amid Invisible Pollution”

Figures

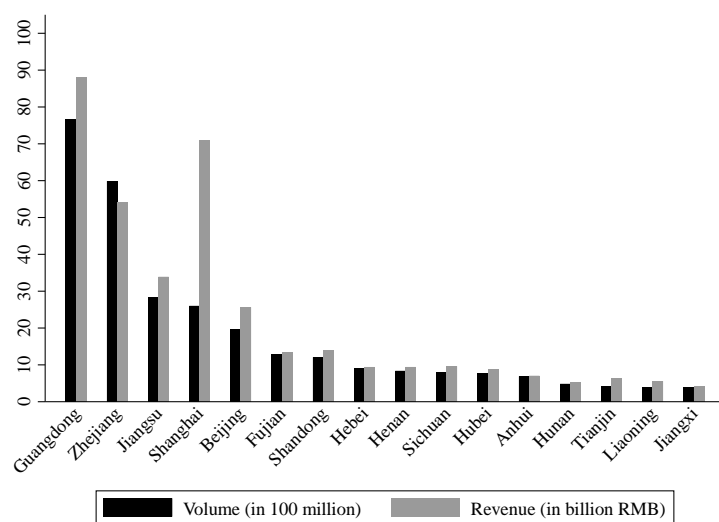


Figure 1: Delivering volume and revenue in different provinces in China, 2016
Source: Report on the Operation of the Postal Industry (2016) by National Postal Office of China.



Figure 2: Size chart of a typical courier car

Source: <https://item.jd.com/>

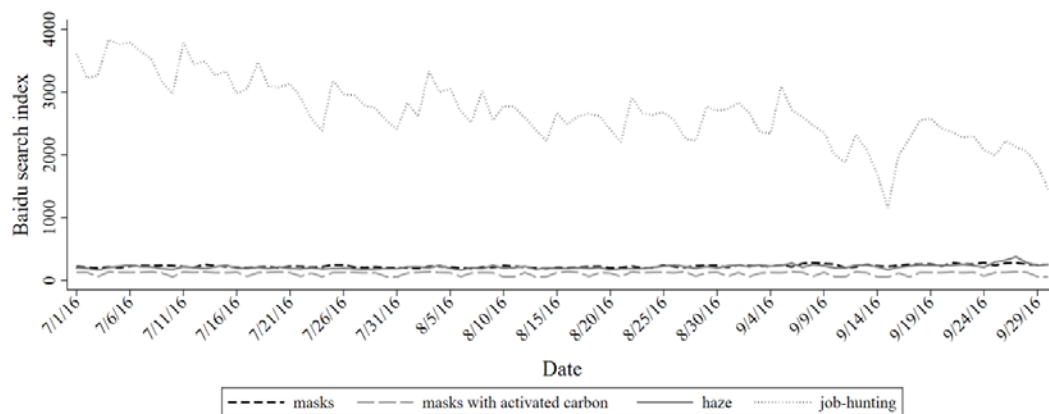


Figure 3: Daily Baidu search index of “masks with activated carbon”, “masks”, “haze”, and “job searching” for Guangdong Province from July 1 to September 30, 2016.

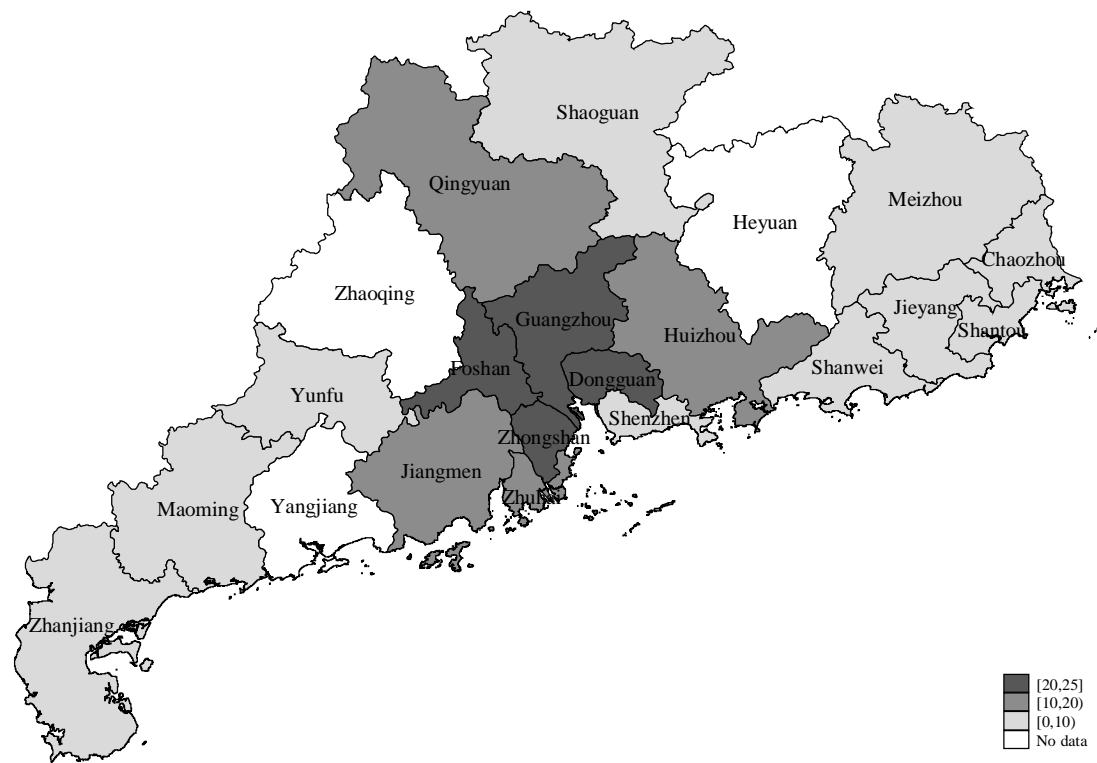


Figure 4: Number of days with an AQI over 100 (July 1 to September 30, 2016) in the prefecture-level cities of Guangdong province, China. Source: National Environmental Monitoring Center of China

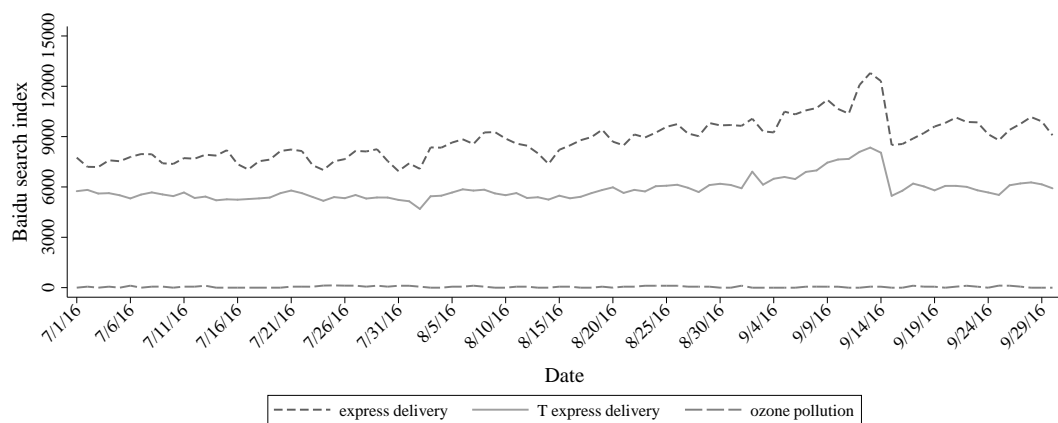


Figure 5: Daily Baidu search index of “express delivery”, “*T* express delivery”, and “ozone pollution” for Guangdong Province from July 1 to September 30, 2016.

Tables

Table 1: Index and concentration breakpoints for six air pollutants

| IAQI | Ozone (max. 8h avg.) | CO (24h avg.) | PM ₁₀ (24h avg.) | PM _{2.5} (24h avg.) | SO ₂ (24h avg.) | NO ₂ (24h avg.) |
|--|----------------------|---------------|-----------------------------|------------------------------|----------------------------|----------------------------|
| 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 50 | 100 | 2 | 50 | 35 | 50 | 40 |
| 100 | 160 | 4 | 150 | 75 | 150 | 80 |
| 150 | 215 | 14 | 250 | 115 | 475 | 180 |
| 200 | 265 | 24 | 350 | 150 | 800 | 280 |
| 300 | 800 | 36 | 420 | 250 | 1600 | 565 |
| 400 | -- | 48 | 500 | 350 | 2100 | 750 |
| 500 | -- | 60 | 600 | 500 | 2620 | 940 |
| max. value in the sample | 300 | 1.7 | 125 | 88 | 46 | 67 |
| IAQI calculated from the max. value of the pollutant in the sample | 207 | 42.5 | 87.5 | 116.25 | 46 | 83.75 |

Notes: The unit for CO is mg/m³, and the units for the five other pollutants are µg/m³. IAQI of ozone (max. 8h avg.) is not calculated if the concentration of ozone (max. 8h avg.) exceeds 800 µg/m³.

Table 2: The number of couriers and average labor productivity in different cities

| City | Number of couriers | Average delivery volume |
|-----------|--------------------|-------------------------|
| Chaozhou | 15 | 78.22 |
| Dongguan | 46 | 108.31 |
| Foshan | 50 | 108.83 |
| Guangzhou | 436 | 123.60 |
| Huizhou | 74 | 124.18 |
| Jiangmen | 44 | 54.56 |
| Jieyang | 21 | 40.27 |
| Maoming | 13 | 72.13 |
| Meizhou | 10 | 116.01 |
| Qingyuan | 29 | 134.65 |
| Shantou | 11 | 112.68 |
| Shanwei | 2 | 33.57 |
| Shaoguan | 47 | 75.80 |
| Shenzhen | 559 | 92.54 |
| Yunfu | 1 | 27.14 |
| Zhanjiang | 146 | 63.47 |
| Zhongshan | 4 | 25.27 |
| Zhuhai | 3 | 32.91 |
| Total | 1511 | 101.57 |

Source: Department of Human Resources of *T* Company Guangdong Office.

Table 3: Correlation coefficients between air pollutants in the sample

| | AQI | PM _{2.5} | PM ₁₀ | SO ₂ | CO | NO ₂ | Ozone (max. 8h avg.) |
|-------------------------|-------|-------------------|------------------|-----------------|-------|-----------------|-------------------------|
| AQI | 1 | | | | | | |
| PM _{2.5} | 0.764 | 1 | | | | | |
| PM ₁₀ | 0.770 | 0.969 | 1 | | | | |
| SO ₂ | 0.458 | 0.585 | 0.621 | 1 | | | |
| CO | 0.258 | 0.464 | 0.463 | 0.406 | 1 | | |
| NO ₂ | 0.536 | 0.566 | 0.533 | 0.333 | 0.286 | 1 | |
| Ozone (max. 8h avg.) | 0.958 | 0.723 | 0.730 | 0.419 | 0.219 | 0.416 | 1 |

Table 4: Average concentrations of six air pollutants in the sample and the first-class and second-class standards in China

| | Average concentration | First-class standard | Second-class standard |
|--|-----------------------|----------------------|-----------------------|
| Ozone (max. 8 h avg.) ($\mu\text{g}/\text{m}^3$) | 101.46 | 100 | 160 |
| PM _{2.5} ($\mu\text{g}/\text{m}^3$) | 27.2 | 35 | 75 |
| PM ₁₀ ($\mu\text{g}/\text{m}^3$) | 45.06 | 50 | 150 |
| SO ₂ ($\mu\text{g}/\text{m}^3$) | 11.82 | 50 | 150 |
| NO ₂ ($\mu\text{g}/\text{m}^3$) | 23.01 | 80 | 80 |
| CO (mg/m^3) | 0.81 | 4 | 4 |

Source: Self calculation and China's *Ambient Air Quality Standards* (GB 3095–2012).

Table 5: Robustness check: Effects of ozone on labor productivity using an IV constructed from NO₂ in upwind nearby cities

| | (1) | (2) | (3) | (4) |
|--|------------------------|-----------------------|-----------------------|-----------------------|
| Second Stage (Dependent variable: Log (Delivery Volume)) | | | | |
| Ozone/10 | -0.0302*** (0.0077) | -0.0155** (0.0070) | -0.0177** (0.0068) | -0.0180** (0.0084) |
| First Stage (Dependent variable: Ozone/10) | | | | |
| NO ₂ source/10 | 0.1632*** (0.0400) | 0.1566*** (0.0362) | 0.1569*** (0.0357) | 0.1632*** (0.0362) |
| Wald F statistic | 16.681 | 18.747 | 19.349 | 20.517 |
| Individual FE | Yes | No | Yes | No |
| Month FE | No | Yes | Yes | Yes |
| Day-of-week FE | No | Yes | Yes | Yes |
| Subsidiary FE | No | Yes | No | Yes |
| Individual characteristics | No | No | No | Yes |
| Observations | 66374 | 66374 | 66374 | 36496 |

Notes: The sample consists of worker–day observations. Standard errors two-way clustered by worker and date are reported in parentheses. All regressions are estimated by 2SLS. All regressions control dummy variables of daily maximum temperature, solar radiation, dummy variables of maximum temperature \times solar radiation, precipitation, maximum wind speed, atmospheric pressure, and relative humidity at the daily level. Wald F statistic refers to the Kleibergen–Paap rk Wald F statistic, which is used to check the existence of weak IV.

Table 6: Robustness check: using different nearby cities to construct IV

| | Include cities within 50 km | | Exclude cities within 100 km | |
|-----------------------------|-----------------------------|------------------------|------------------------------|-----------------------|
| | (1) | (2) | (3) | (4) |
| | Second stage estimation | | Second stage estimation | |
| Ozone /10 | -0.0182*** (0.0042) | | -0.0160** (0.0066) | |
| AQI/10 | | -0.0224*** (0.0055) | | -0.0185** (0.0078) |
| Individual FE | Yes | Yes | Yes | Yes |
| Month FE | Yes | Yes | Yes | Yes |
| Day-of-week FE | Yes | Yes | Yes | Yes |
| | First stage estimation | | First stage estimation | |
| Ozone _{source} /10 | 0.6138*** (0.0959) | | 0.2721*** (0.0646) | |
| AQI _{source} /10 | | 0.6802*** (0.1089) | | 0.3541*** (0.0739) |
| Wald F statistic | 40.987 | 39.011 | 17.720 | 22.962 |
| Observations | 66374 | 66374 | 66374 | 66374 |

Notes: The sample consists of worker–day observations. The standard errors clustered by worker and date are reported in parentheses. All regressions are estimated by 2SLS. All regressions control dummy variables of daily maximum temperature, solar radiation, dummy variables of maximum temperature \times solar radiation, precipitation, maximum wind speed, atmospheric pressure, and relative humidity at the daily level.

Table 7: Additional robustness checks

| | (1) | (2) | (3) | (4) | (5) | (6) |
|--------------------------|------------------------|------------------------|------------------------|------------------------|--------------------------------|------------------------|
| | Truncated sample | | Control Typhoon | | Add future pollution variables | |
| Ozone/10 | -0.0200*** (0.0049) | | -0.0187*** (0.0046) | | -0.0224*** (0.0072) | |
| AQI/10 | | -0.0246*** (0.0064) | | -0.0227*** (0.0060) | | -0.0295*** (0.0112) |
| Ozone _{t+1} /10 | | | | | 0.0010 (0.0007) | |
| AQI _{t+1} /10 | | | | | | 0.0015 (0.0012) |
| Individual FE | Yes | Yes | Yes | Yes | Yes | Yes |
| Month FE | Yes | Yes | Yes | Yes | Yes | Yes |
| Day-of-week FE | Yes | Yes | Yes | Yes | Yes | Yes |
| Observations | 58940 | 58940 | 66374 | 66374 | 65619 | 65619 |

Notes: The sample consists of worker–day observations. All regressions are estimated by 2SLS. We construct the IVs for AQI and ozone using the same method as that in the previous result tables. Standard errors two-way clustered by worker and date are reported in parentheses. All regressions control dummy variables of daily maximum temperature, solar radiation, dummy variables of maximum temperature \times solar radiation, precipitation, maximum wind speed, atmospheric pressure, and relative humidity at the daily level.

Table 8: Big sales dates of top five electronic business platforms in China

| Electronic business platform | Name of the promotion activity | Dates |
|--|---|----------|
| Taobao (including Tmall, Tmall international, Juhuasuan, and other platforms of the Alibaba group) | Tmall New Year Festival | 1.22-2.2 |
| | 618 Carnival for Fans | 6.18 |
| | Double 11 | 11.11 |
| | Double 12 | 12.12 |
| Jingdong | 618 Carnival | 6.18 |
| | Double 11 | 11.11 |
| | Double 12 | 12.12 |
| Vipshop | Mid-year promotion | 6.16 |
| | Vipshop anniversary | 12.8 |
| | Double 11 | 11.11 |
| Suning.com | Shopping festival for electrical appliances | 4.18 |
| | Celebration of Suning | 8.18 |
| | Double 11 | 11.11 |
| GOME | GOME Black Friday | 3.11 |

Table 9: Effects of air pollution on labor supply

| | (1) | (2) | (3) | (4) | (5) | (6) |
|----------------------|----------------------|---------------------|-----------------------|-----------------------|---------------------|---------------------|
| ozone | 1.05e-07 (0.0001) | -0.0001 (0.0001) | -3.00e-05 (0.0001) | | | |
| ozone _{t-1} | | | -0.0001 (0.0001) | | | |
| AQI | | | | -1.53e-05 (0.0001) | -0.0001 (0.0001) | -0.0001 (0.0001) |
| AQI _{t-1} | | | | | | -0.0001 (0.0001) |
| Individual FE | Yes | Yes | Yes | Yes | Yes | Yes |
| Month FE | No | Yes | Yes | No | Yes | Yes |
| Day-of-week FE | No | Yes | Yes | No | Yes | Yes |
| Observations | 129187 | 129187 | 129187 | 129187 | 129187 | 129187 |

Notes: The sample consists of worker–day observations. The dependent variable is a dummy variable of whether the courier works that day or not. Standard errors two-way clustered by worker and date are reported in parentheses. All regressions control dummy variables of daily maximum temperature, solar radiation, dummy variables of maximum temperature \times solar radiation, precipitation, maximum wind speed, atmospheric pressure, and relative humidity at the daily level.

Table 10: Heterogeneous effects of AQI on labor productivity

| | (1) | (2) | (3) | (4) | (5) |
|---|------------------------|-----------------------|------------------------|------------------------|------------------------|
| AQI | -0.0207*** (0.0073) | -0.0180** (0.0077) | -0.0189*** (0.0072) | -0.0256*** (0.0077) | -0.0258*** (0.0078) |
| AQI \times 30 years old or above | -0.0061 (0.0066) | | | | |
| AQI \times High school and above | | -0.0078 (0.0059) | | | |
| AQI \times career duration longer than 1 year | | | -0.0121 (0.0074) | | |
| AQI \times <i>Hukou</i> in Guangdong | | | | 0.0078 (0.0066) | |
| AQI \times work in the hometown | | | | | 0.0290** (0.0135) |
| Individual FE | Yes | Yes | Yes | Yes | Yes |
| Month FE | Yes | Yes | Yes | Yes | Yes |
| Week FE | Yes | Yes | Yes | Yes | Yes |
| Observations | 36496 | 36496 | 36496 | 36496 | 26920 |

Notes: The sample consists of worker–day observations. All regressions are estimated by 2SLS. The standard errors clustered by worker and date are reported in parentheses. All regressions control dummy variables of daily maximum temperature, solar radiation, dummy variables of maximum temperature \times solar radiation, precipitation, maximum wind speed, atmospheric pressure, and relative humidity at the daily level.

Table 11: Effects of AQI on labor productivity across couriers with different average productivities

| | | (1) | (2) | (3) |
|---|--|---------------------|------------------------|------------------------|
| Average daily delivery volume | | Lowest 33% | 33%-67% | Top 33% |
| Panel A: Dependent variable: Delivery Volume | | | | |
| AQI/10 | | -0.1175 (0.3576) | -1.4150*** (0.4552) | -2.6287*** (0.6906) |
| Panel B: Dependent variable: Log (Delivery Volume) | | | | |
| AQI /10 | | 0.0028 (0.0088) | -0.0251*** (0.0079) | -0.0280*** (0.0074) |
| Individual FE | | Yes | Yes | Yes |
| Month FE | | Yes | Yes | Yes |
| Day-of-week FE | | Yes | Yes | Yes |
| Observations | | 12685 | 25042 | 28647 |

Notes: Each cell represents the coefficient from a separate regression that estimates the effect of AQI on courier productivity. The sample consists of worker–day observations. Dependent variable is the daily delivery volume of each courier. All regressions are estimated by 2SLS. Standard errors two-way clustered by worker and date are reported in parentheses. All regressions control dummy variables of daily maximum temperature, solar radiation, dummy variables of maximum temperature \times solar radiation, precipitation, maximum wind speed, atmospheric pressure, and relative humidity at the daily level.

Table 12: Cumulative effects of ozone (PDL model)

| | (1) | (2) | (3) | (4) |
|--------------------------------------|------------------------|------------------------|------------------------|------------------------|
| | PDL (K, 2) | | PDL (K, 3) | |
| | OLS | 2SLS | OLS | 2SLS |
| <i>Different lags of daily ozone</i> | | | | |
| $5(\sum_0^5 \lambda_k)$ | -0.0097*** (0.0016) | -0.0110** (0.0048) | -0.0098*** (0.0017) | -0.0145*** (0.0046) |
| $10(\sum_0^{10} \lambda_k)$ | -0.0014 (0.0021) | -0.0732 (0.1005) | -0.0014 (0.0020) | 0.0022 (0.0070) |
| $15(\sum_0^{15} \lambda_k)$ | -0.0075** (0.0036) | -0.0508*** (0.0146) | -0.0063* (0.0034) | -0.0141** (0.0057) |
| $20(\sum_0^{20} \lambda_k)$ | -0.0205*** (0.0044) | -0.0434*** (0.0097) | -0.0190*** (0.0044) | -0.0347*** (0.0080) |
| $25(\sum_0^{25} \lambda_k)$ | -0.0254*** (0.0056) | -0.0605*** (0.0147) | -0.0245*** (0.0056) | -0.0602*** (0.0139) |
| $30(\sum_0^{30} \lambda_k)$ | -0.0363*** (0.0076) | -0.0818*** (0.0177) | -0.0352*** (0.0074) | -0.0787*** (0.0188) |
| $35(\sum_0^{35} \lambda_k)$ | -0.0381*** (0.0080) | -0.0614*** (0.0169) | -0.0393*** (0.0080) | -0.0632*** (0.0167) |
| Individual FE | Yes | Yes | Yes | Yes |
| Month FE | Yes | Yes | Yes | Yes |
| Day-of-week FE | Yes | Yes | Yes | Yes |

Notes: The sample consists of worker–day observations. Each cell represents the sum of the coefficients on daily ozone concentrations (in $10 \mu\text{g}/\text{m}^3$) of a certain number of preceding days in the corresponding regression. Standard errors two-way clustered by worker and date are reported in parentheses. All regressions control dummy variables of daily maximum temperature, solar radiation, dummy variables of maximum temperature \times solar radiation, precipitation, maximum wind speed, atmospheric pressure, and relative humidity at the daily level.

Table 13: Cumulative effects of AQI (PDL model)

| | (1) | (2) | (3) | (4) |
|------------------------------------|------------------------|------------------------|------------------------|------------------------|
| | PDL (K, 2) | | PDL (K, 3) | |
| | OLS | 2SLS | OLS | 2SLS |
| <i>Different lags of daily AQI</i> | | | | |
| $5(\sum_0^5 \lambda_k)$ | -0.0150*** (0.0025) | -0.0186*** (0.0054) | -0.0150*** (0.0026) | -0.0225*** (0.0060) |
| $10(\sum_0^{10} \lambda_k)$ | -0.0029 (0.0035) | -0.0295 (0.0197) | -0.0029 (0.0035) | -0.0001 (0.0093) |
| $15(\sum_0^{15} \lambda_k)$ | -0.0127** (0.0053) | -0.0517*** (0.0165) | -0.0104* (0.0054) | -0.0170* (0.0086) |
| $20(\sum_0^{20} \lambda_k)$ | -0.0285*** (0.0065) | -0.0496*** (0.0121) | -0.0267*** (0.0064) | -0.0416*** (0.0108) |
| $25(\sum_0^{25} \lambda_k)$ | -0.0375*** (0.0081) | -0.0797*** (0.0179) | -0.0350*** (0.0082) | -0.0792*** (0.0193) |
| $30(\sum_0^{30} \lambda_k)$ | -0.0528*** (0.0109) | -0.1148*** (0.0231) | -0.0496*** (0.0107) | -0.1000*** (0.0302) |
| $35(\sum_0^{35} \lambda_k)$ | -0.0548*** (0.0115) | -0.0936*** (0.0218) | -0.0562*** (0.0115) | -0.0960*** (0.0213) |
| Individual FE | Yes | Yes | Yes | Yes |
| Month FE | Yes | Yes | Yes | Yes |
| Day-of-week FE | Yes | Yes | Yes | Yes |

Notes: The sample consists of worker–day observations. Each cell represents the sum of the coefficients on daily AQI/10 of a certain number of preceding days in the corresponding regression. Standard errors two-way clustered by worker and date are reported in parentheses. All regressions control dummy variables of daily maximum temperature, solar radiation, dummy variables of maximum temperature \times solar radiation, precipitation, maximum wind speed, atmospheric pressure, and relative humidity at the daily level.

Table 14: Estimated welfare loss at the individual level

| Cities | Income Loss (yuan/person) | Cities | Income Loss (yuan/person) |
|-----------|---------------------------|-----------|---------------------------|
| Dongguan | 1154 | Zhanjiang | 585 |
| Foshan | 1114 | Shenzhen | 583 |
| Jiangmen | 1057 | Shaoguan | 581 |
| Guangzhou | 943 | Huizhou | 580 |
| Zhongshan | 931 | Shanwei | 554 |
| Qingyuan | 868 | Jieyang | 484 |
| Zhaoqing | 852 | Heyuan | 382 |
| Zhuhai | 748 | Yunfu | 295 |
| Chaozhou | 738 | Maoming | 270 |
| Yangjiang | 679 | Meizhou | 220 |
| Shantou | 596 | | |

Notes: Welfare loss refers to the income loss for a courier caused by air pollution in 2016. See equation (11) for the calculation method.

Table 15: Estimated welfare loss at the city level for top 50 cities in the express industry in China

| City | Loss (10 thousand yuan) | City | Loss (10 thousand yuan) |
|--------------|-------------------------|-----------|-------------------------|
| Guangzhou | 27009 | Shantou | 2179 |
| Jinhua | 20257 | Zhongshan | 2006 |
| Shenzhen | 12088 | Taizhou | 1989 |
| Hangzhou | 11324 | Wenzhou | 1855 |
| Beijing | 10262 | Xi'an | 1780 |
| Shanghai | 8989 | Huzhou | 1742 |
| Dongguan | 8279 | Suqian | 1629 |
| Suzhou | 6290 | Shaoxing | 1562 |
| Wuhan | 4832 | Chongqing | 1554 |
| Zhengzhou | 4621 | Xingtai | 1424 |
| Jieyang | 4089 | Nantong | 1393 |
| Shijiazhuang | 4055 | Langfang | 1383 |
| Nanjing | 4014 | Xuzhou | 1326 |
| Tianjin | 3789 | Changzhou | 1243 |
| Wuxi | 3719 | Qingdao | 1219 |
| Chengdu | 3153 | Weifang | 1205 |
| Baoding | 3116 | Shenyang | 943 |
| Jinan | 3094 | Fuzhou | 898 |
| Foshan | 3027 | Nanchang | 886 |
| Ningbo | 2866 | Huizhou | 766 |
| Quanzhou | 2810 | Xiamen | 750 |
| Jiaxing | 2742 | Chaozhou | 630 |
| Linyi | 2602 | Kunming | 464 |
| Hefei | 2592 | Nanning | 344 |
| Changsha | 2327 | Ha'erbin | 220 |

Notes: Welfare loss refers to the income loss for a courier caused by air pollution in 2019. See Equation (12) for the calculation method.