Highway toll and air pollution: Evidence from Chinese cities

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Contents

Introduction

- Vehicles generate several negative externalities, such as traffic congestion, air pollution, and traffic accidents (Parry et al., 2007), but much attention has focused on congestion externalities.
- To reduce traffic congestion to the socially-optimal level, a toll equal to congestion externalities should be charged (Walters, 1961).
- The congestion pricing theory has been modeled in various ways but few models consider pollution externalities resulting from vehicle emissions.
- Arnott and Kraus (2003) provide an excellent introduction to highway congestion pricing theory and it is not hard to add vehicle pollution externalities to their model

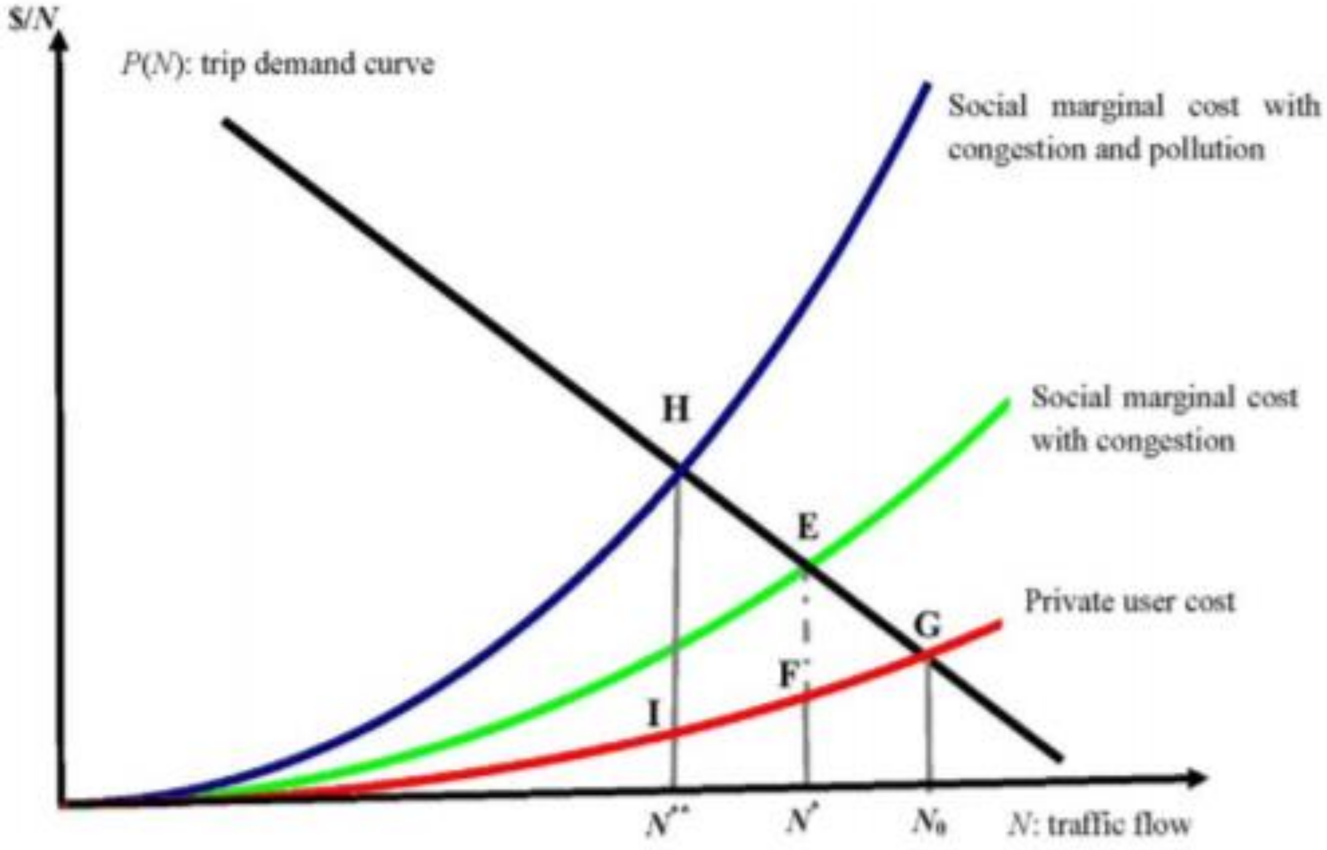

Fig. 1. Optimal toll, congestion and pollution externalities.

- Congestion pricing has been practiced in some cities (for example, London and Stockholm), but empirical evidence on its effect on air pollution is scant.
- Daniel and Bekka (2000) adapt TRANPLAN, a widely used highway-modeling program, to simulate the effect of congestion pricing on vehicle emissions using data from New Castle County, Delaware.
- Mitchell et al. (2005) simulate the impact of different road pricing schemes on air quality using data from Leeds, UK.
- Anas and Lindsey (2011) review a few simulation and estimation studies in London, Stockholm, and Milan.
- These studies show that tolls can reduce vehicle. No similar studies have been conducted in China. This study uses data from the removal of highway tolls in urban China and demonstrates that tolls can substantially reduce air pollution.

- China's highway network has grown rapidly: expressway mileage grew from 522 km in 1990 to 41,005 in 2005, and is expected to reach 85,000 by 2020 (Yang and Lee, 2008, p. 1).
- Urban air pollution is a serious issue in China. Vehicles are one of the major contributors to urban air pollution in China (Cai and Xie, 2007).
- For example, in Beijing, vehicles are responsible for at least 23% of particulate matter.A large proportion of vehicles travel on highways and most of these are passenger vehicles. Removing highway tolls will lead to socially-excessive passenger vehicle travel due to more congestion and more emissions.

- We use a quasi-natural experiment in China to study the effect of removing highway tolls on urban air pollution. On July 24, 2012, the China State Council announced that highway tolls would be waived for passenger vehicles with fewer than eight seats during four official holidays: Spring Festival, Tomb-Sweeping Day, Labor Day (May 1), and National Day (October1), beginning with National Day 2012. There are eight days during the 2012 National Day holiday (September 30 to October 7, 2012), when highway tolls were first waived. We use the seven-day National Day holiday in 2011 (October 1 to October 7, 2011) as the comparison. It is worth noting that the only difference between the 2011 and 2012 National Day holidays is the highway toll waiver; there is no other nationwide policy during these two holidays that affects air quality.

- Using the daily air pollution and weather data for 98 major cities in China for 2011 and 2012 to identify the effects of removing highway tolls on urban air pollution.
- To control for unobserved confounding factors that may affect daily air quality, we employ both a panel regression discontinuity design method and a differences-in-differences method with the 2011 National Day holiday as a comparison.
- The findings suggest that removing highway tolls lowers social welfare.

- The study complements not only the limited empirical evidence on congestion pricing's effect on air pollution but also the literature on alternative road pricing, such as a gasoline tax.
- Compared with vehicle emission pricing or other externality tax, a gasoline tax is administratively simple and has been adopted in many countries.
- Although gasoline tax is not placed on emissions, miles travelled, or peak-period congestion, an optimal gasoline tax should take into account the external costs of congestion, air pollution, and accidents.
- A few studies estimate consumers’ response to gasoline tax but direct empirical evidence on the effect of gasoline tax on air pollution is scarce. The estimated toll elasticity of pollution is in line with the implied gasoline tax elasticity of pollution.

Data

- The two main data sets we use are the daily air pollution index (API) data and the daily weather conditions for major cities in China.
- The concentrations of three pollutants measured at monitoring stations within a city: PM_{10}, nitrogen dioxide (NO_2), and sulfur dioxide (SO_2).
- Focusing on the sample period from January 1, 2011 to December 31, 2012 but also expand the sample back to 2009 for robustness checks and placebo tests.
- After January 1, 2013, the MEP stopped publishing the API and switched to a new air quality index (AQI) for 74 cities.

- When the API is above 50, the major pollutant is identified. PM_{10} is the major pollutant for most of the days in most of cities and vehicles are the major creator of PM_{10} in cities. For example, approximately 53% of Beijing's PM_{10} is attributable to motor vehicles: 23% due to auto emissions and 30% road dust (Hao et al., 2005)
- PM_{10} has a linear piecewise relationship with API (Andrews, 2008):

$$PM10 = API, \quad 0 \leq API \leq 50;$$
$$PM10 = 2*API - 50, \quad 50 \leq API \leq 200;$$
$$PM10 = (7/10)*API + 210, \quad 200 \leq API \leq 300;$$
$$PM10 = (4/5)*API + 180, \quad 300 \leq API \leq 400;$$
$$PM10 = API + 100, \quad 400 \leq API \leq 500.$$

- Using both the API and the imputed PM_{10} to test the effect of waiving highway tolls.
- Weather conditions influence emissions and air quality.
- PM_{10} concentration is affected by precipitation and wind speed (Rost et al., 2009; Jones et al., 2010) and ozone is not easily formed on cloudy, cool, rainy, or windy days.
- Daily weather conditions include wind speed, humidity, temperature, and precipitation and are downloaded from the website 〈*www. wunderground.com*〉.
- The weather data also include visibility, which is closely related to air pollution.
- By the end of 2008, about 95% of expressways in China are tolled. Toll rates differ across provinces, highways, and vehicle types.

- Because of this complexity of the toll rate structure we need to construct a “toll index” for each city to estimate the toll elasticity of air pollution.
- Merging the air pollution and weather data and dropping cities without any tolled expressways passing by provides a final sample of 98 cities in 31 provinces (or province-level cities).
- Fig. 2 shows the map of these 98 cities and the highways connecting them.
- Table 1 presents the summary statistics of key variables.

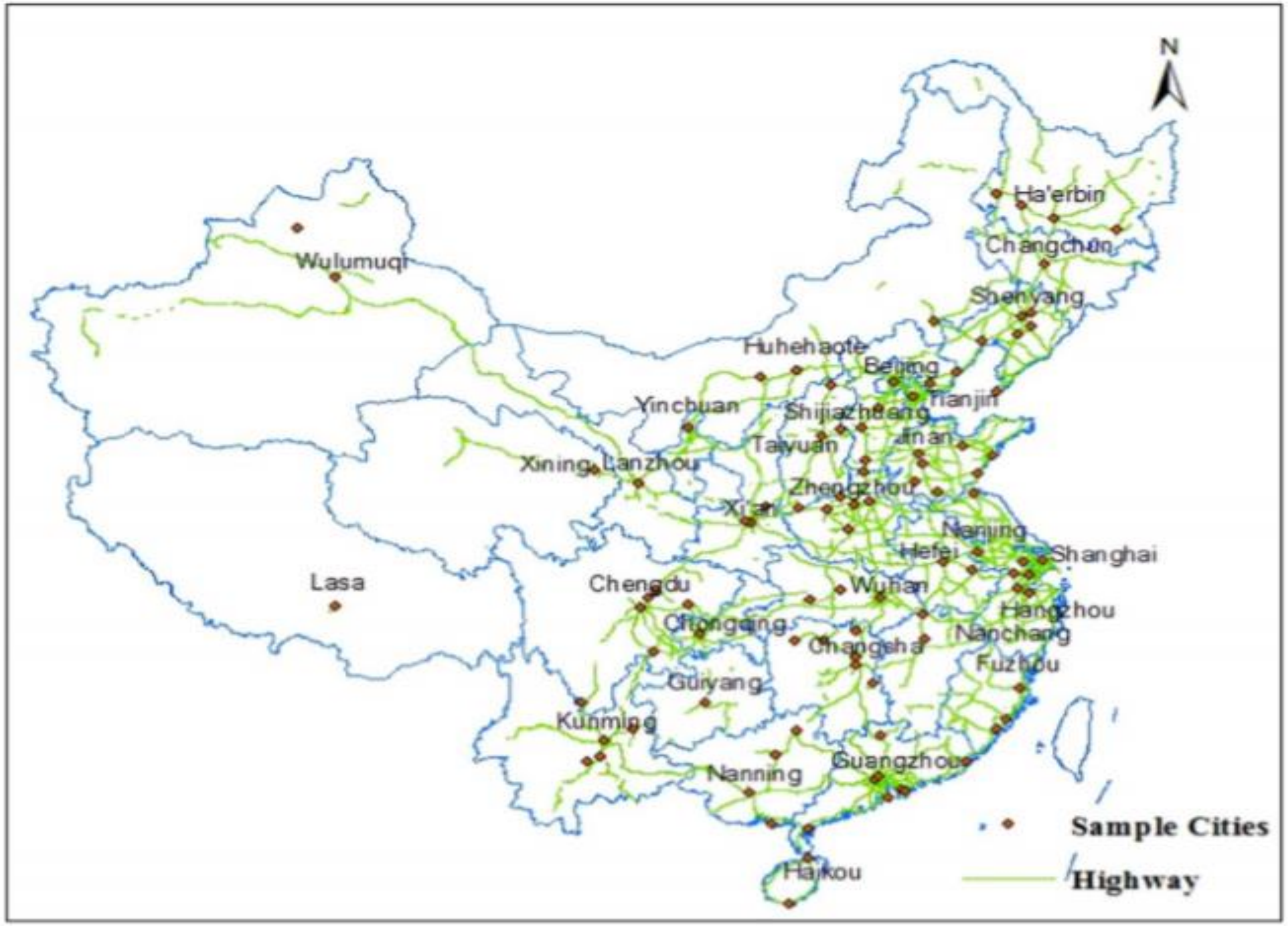

Fig. 2. Cities in our sample and highways connecting them.

Table 1
Summary statistics.

Variable	Mean (standard deviation): 2011–2012	2011 National Day holiday period	2012 National Day holiday period	*t* test statistic
Air pollution index	65.7(27.5)	55.2	67	−10.0
PM_{10} ($\mu g/m^3$)	84.1 (48.1)	67	86	−9.1
Visibility(km)	11.6 (7.3)	12.2	11.8	1.1
Maximum wind speed (km/h)	7.9 (4.5)	8.1	6.3	7.7
Precipitation (mm)	1.4 (6.0)	1.6	0.5	4.0
Average humidity (%)	61.1 (20.3)	62.6	59.9	3.0
Average temperature (cel.)	14.6 (11.4)	16.5	18.2	−7.5
National day holiday dummy	0.02(0.14)			
Notoll dummy	0.01 (0.10)			
Weekend dummy	0.29 (0.45)			
Other holidays dummy	0.05 (0.23)			

Note: The *t* test statistics in the last column test whether the means of a variable in the 2011 and 2012 National Day holiday periods are equal.

Model specifications

- Since both production and consumption activities generate air pollution and holidays alter the proportion of these two types of activities, we need to separate the holiday effect.
- Using the 2011 National Day holiday, from October 1 to October 7, during which highway tolls were charged, as a control group.
- The main model is a city fixed effect, panel data model:

$$P_{it} = \alpha_i + \beta_1 \, Nationalday + \beta_2 \, Notoll + \gamma W_{it} + \theta X_{it} + f(t) + \varepsilon_{it}, \quad (1)$$

- Ideally, gasoline prices should be included too. However, gasoline prices are regulated by the central government and their changes are not coincident with the “Notoll” period.In addition, the inclusion of year fixed effects and flexible time trends absorbs well these gasoline price shocks.
- During recent years, high-speed train has become a popular commuting mode in many Chinese cities. Drivers in cities with high-speed train lines or stations are likely to be more sensitive to trip cost due to substitution between commuting modes.
- We test this effect heterogeneity by estimating Model (1) for two subsamples: cities with at least one high-speed train line passing through in both 2011 and 2012 and cities without any high-speed train lines in both years.

- For the RDD estimation, f(t) is prefered to be a local linear or quadratic polynomial term.
- Gelman and Zelizer (2015) examine two published studies and demonstrate that RDD estimates may be very sensitive to high-order polynomials of the assignment variable.
- Focusing on the estimates using local linear and quadratic regressions but also report the estimates using global polynomial regressions.
- Reassuringly, both approaches generate very similar results.

Results

- 1.1 Suggestive results
- 1.2 Results from panel DID design
- 1.3 PM_{10} and visibility results
- 1.4 Testing the intertemporal shift of travel demand
- 1.5 Placebo test and sensitivity test
- 1.6 Estimating the toll elasticity of pollution

1.1 Suggestive results

- We first estimate Model (1) separately for the 2011 and 2012 subsamples. We must drop the Notoll variable because tolls were charged on all days of the 2011 National Day holiday and in 2012 the days without tolls coincided with the National Day holiday. We treat the National Day holiday as an exogenous “policy” and apply the RDD method, using flexible time trends to control for unobserved confounding factors that affect urban air pollution. These estimates can show whether the National Day holidays affect air pollution differently in 2011 and 2012.

Table 2
National Day holiday effect by year.

Variable	1	2	3	4	5	6
Panel 1: Dependent variable: log(API). Sample period: 2011						
Nationalday	−0.206***	−0.182***	−0.113***	−0.115***	−0.099***	−0.085**
	(−5.21)	(−5.14)	(−3.30)	(−3.35)	(−2.68)	(−2.02)
Time trend	No	1st order	2nd order	3rd order	4th order	5th order
Adjusted R^2	0.371	0.372	0.382	0.386	0.386	0.386
AIC	18,414	18,354	17,792	17,592	17,577	17,569
Panel 2: Dependent variable: log(API). Sample period: 2012						
Nationalday	−0.047*	−0.041*	−0.008	−0.008	−0.006	0.039
	(−1.85)	(−1.68)	(−0.28)	(−0.30)	(−0.23)	(−1.40)
Time trend	No	1st order	2nd order	3rd order	4th order	5th order
Adjusted R^2	0.399	0.399	0.403	0.403	0.403	0.406
AIC	17,461	17,455	17,221	17,219	17,220	16,988

Note: Weather variables, month-of-year dummies, weekend dummy, other holidays dummy, and city fixed effects (98 cities) are included. Column 1 does not include any time trend. Columns 2 to 6 include polynomial time trend terms up to the fifth order. *t* statistics are in the parentheses. Standard errors are clustered at the province level (31 clusters). AIC denotes the statistics for Akaike's information criterion. Sample sizes for 2011 and 2012 are 34,728 and 35,672, respectively.

* Superscripts indicate significance at the 10% levels, respectively.

** Superscripts indicate significance at the 5% levels, respectively.

*** Superscripts indicate significance at the 1% levels, respectively.

- To check whether the above suggestive results are sensitive to the window width before and after the “policy”, we also employ the RDD method with local linear or quadratic regressions to estimate the difference in air pollution before, during, and after the National Day holidays with a symmetric, narrow window.
- Specifically, we regress log(API) on the Nationalday dummy, weekend dummy, four daily weather variables, city fixed effects, and linear or quadratic time trends before, during, and after the “policy”, using a small window of seven days before, during, and after the National Day holiday in 2011. We estimate the same model using a small window of eight days before, during, and after the National Day holiday in 2012.

Table 3
Symmetric window RDD results.

Variable	1	2	3
Panel 1: Symmetric window (seven days) before, during, and after the National Day holiday in 2011			
Nationalday	−0.086**	−0.076*	−0.106**
	(−2.00)	(−1.67)	(−2.30)
Time trend	No	1st order	2nd order
Adjusted R^2	0.479	0.492	0.492
AIC	927	880	877
Sample size	2058	2058	2058
Panel 2: Symmetric window (eight days) before, during, and after the National Day holiday in 2012			
Nationalday	0.030	0.054**	0.066**
	(1.39)	(2.33)	(2.07)
Time trend	No	1st order	2nd order
Adjusted R^2	0.394	0.490	0.490
AIC	507	102	105
Sample size	2352	2352	2352

Note: Dependent variable is log(API). Weather variables, weekend dummy, and city fixed effects are included. In Panel 1, the sample includes seven days before, during, and after the National Day holiday in 2011. In Panel 2, the sample includes eight days before, during, and after the National Day holiday in 2012. *t* statistics are in the parentheses. Standard errors are clustered at the province level. AIC denotes the statistics for Akaike's information criterion. Superscripts "***" indicate significance at the 1% levels, respectively.

* Superscripts indicate significance at the 10% levels, respectively.

** Superscripts indicate significance at the 5% levels, respectively.

- As a visual demonstration, we apply the RDD method and estimate the effect of National Day holiday on air pollution for Shanghai, China's largest city.
- Fig. 3 shows the symmetric quadratic trend seven days before, during, and after the 2011 National Day holiday.
- Fig. 4 shows the symmetric quadratic trend eight days before, during, and after the 2012 National Day holiday.

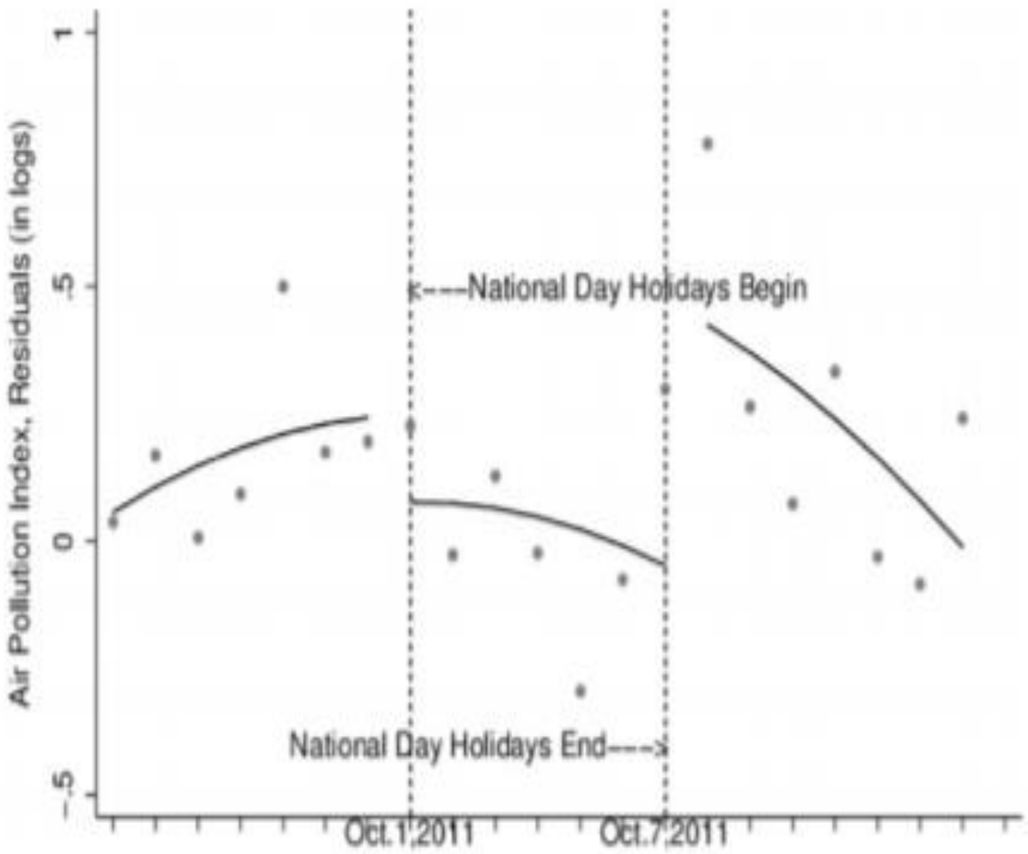

Fig. 3. Time trends seven days before, during, and after the 2011 National Day holiday in Shanghai The plotted dots are the sum of residuals from estimating Eq. (1) in the main text without the *Notoll* dummy and the linear and quadratic time trends. The fitted line allows for a quadratic time trend.

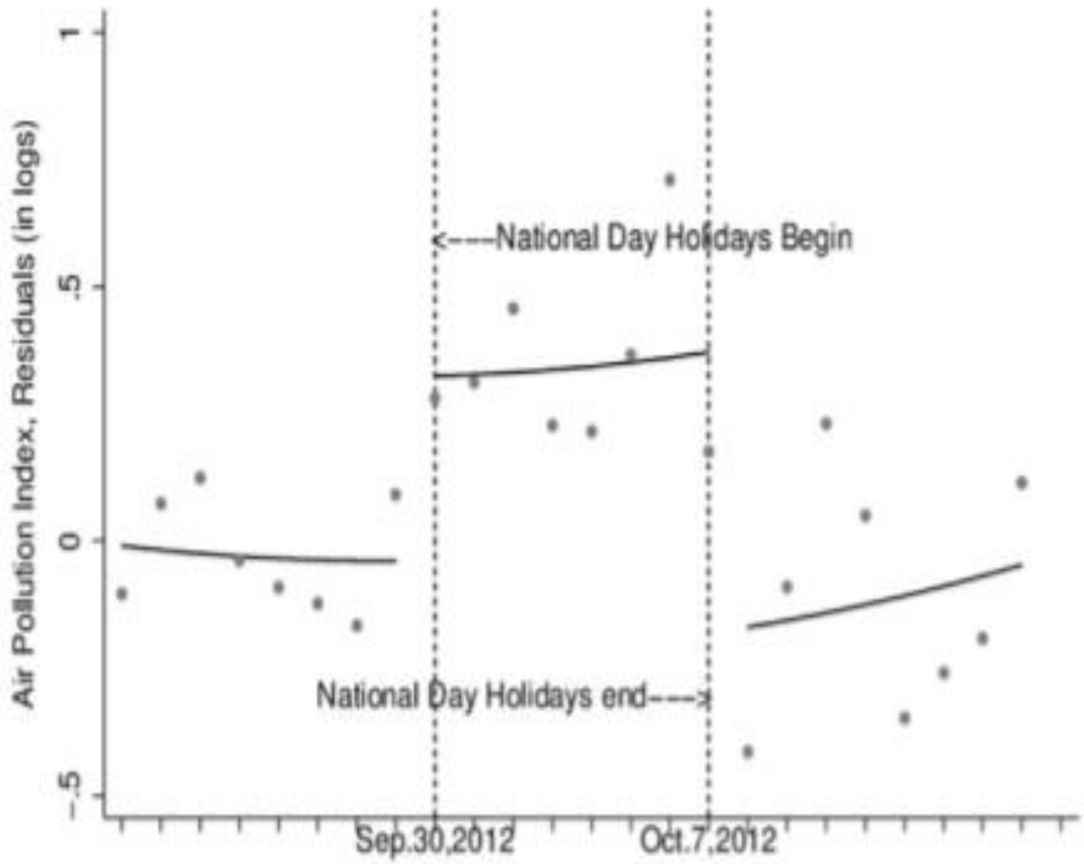

Fig. 4. Time trend eight days before, during, and after the 2012 National Day holiday in Shanghai The plotted dots are the sum of residuals from estimating Eq. (1) in the main text without the *Notoll* dummy and the linear and quadratic time trends. The fitted line allows for a quadratic time trend.

1.2 Results from panel DID design

- To take into account city heterogeneity and to tease out the holiday effect from the “Notoll” effect, we apply the panel differences-indifferences (DID) method.
- Panel 1 of Table 4 reports the estimate results of our main Model (1) using pooled 2011 and 2012 data and a narrow window as in Table 4.
- To facilitate discussion we use the results estimated with a linear time trend as the baseline although the test statistic for Akaike's information criterion (AIC) indicates that the quadratic term is slightly preferred. Table A1 presents the panel data models with global polynomial time trends up to the fourth order and shows that the estimated “Notoll” effects are robust, albeit slightly larger in magnitude

Table 4
Panel data regression results.

Variable	1	2	3
Panel 1: All cities in the sample			
Nationalday	−0.193***	−0.193***	−0.170***
	(−4.39)	(−4.26)	(−4.04)
Notoll	0.153***	0.201***	0.164***
	(3.07)	(3.42)	(2.78)
Weekend	0.037**	0.023	0.028
	(2.13)	(1.21)	(1.52)
Year 2012 dummy	−0.002	1.917	−0.751
	(−0.09)	(1.55)	(−0.35)
Maximum wind speed	−0.014***	−0.014***	−0.014***
	(−3.75)	(−3.67)	(−3.95)
Precipitation	−0.004***	−0.004***	−0.004***
	(−3.57)	(−3.82)	(−3.80)
Average humidity	−0.001	−0.001	−0.000
	(−0.83)	(−0.50)	(−0.06)
Average temperature	0.045***	0.046***	0.049***
	(10.99)	(11.01)	(11.49)
Asymmetric time trend	No	1st order	2nd order
Adjusted R^2	0.420	0.427	0.428
AIC	1785	1736	1725
Sample size	4410	4410	4410
Panel 2: Cities without high-speed train lines in both 2011 and 2012 (46 cities)			
Nationalday	−0.166***	−0.149***	−0.126***
	(−3.49)	(−3.24)	(−3.12)
Notoll	0.125*	0.143**	0.099
	(1.89)	(2.23)	(1.46)
Adjusted R^2	0.387	0.389	0.391
AIC	593	590	587
Sample size	2070	2070	2070
Panel 3: Cities with high-speed train lines in both 2011 and 2012 (40 cities)			
Nationalday	−0.188***	−0.206***	−0.198***
	(−3.30)	(−2.97)	(−2.79)
Notoll	0.160***	0.246***	0.253***
	(2.87)	(2.73)	(2.54)
Adjusted R^2	0.458	0.470	0.469
AIC	882	845	852
Sample size	1800	1800	1800

Table A1
Panel data regression with global polynomial time trends.

Variable	1	2	3	4	5
Nationalday	−0.246***	−0.237***	−0.220***	−0.212***	−0.198***
	(−5.67)	(−5.60)	(−5.29)	(−4.98)	(−5.12)
Notoll	0.232***	0.226***	0.204***	0.215***	0.195***
	(3.92)	(3.69)	(3.26)	(3.15)	(3.13)
Asymmetric time trend	No	1st order	2nd order	3rd order	4th order
Adjusted R^2	0.372	0.373	0.374	0.374	0.375
AIC	37,463	37,400	37,305	37,284	37,191

Note: Dependent variable is log(API). All models also include weather variables, month-of-year dummies, a dummy for holidays other than National Day holiday, a dummy for year 2012, and city fixed effects (98 cities). Column 1 does not include time trend. Columns 2 to 5 include time trends before, during, and after the "no toll" period up to the fourth order. *t* statistics are in the parentheses. Standard errors are clustered at the province level (31 clusters). AIC denotes the statistics for Akaike's information criterion. Superscripts "**", and "*" indicate significance at the 5%, and 10% levels, respectively. Sample size: 70,400.

*** Superscripts indicate significance at the 1% levels, respectively.

- As a visual demonstration, we apply the RDD method and estimate the effect of National Day holiday on air pollution for Shanghai, China's largest city.
- Fig. 3 shows the symmetric quadratic trend seven days before, during, and after the 2011 National Day holiday.
- Fig. 4 shows the symmetric quadratic trend eight days before, during, and after the 2012 National Day holiday.

- To test whether drivers who can substitute driving for train are more responsive to the Notoll policy, we re-estimate panel 1 models for two subsamples.
- cities with at least one high-speed train line passing through in both years and cities without. There are 40 cities that have at least one high-speed train line passing through in both 2011 and 2012, 46 cities that have no high-speed train lines in both 2011 and 2012, and 12 cities that have no high-speed train lines in 2011 but have at least one in 2012.

- The local features and different development stages of cities in China contribute differently to vehicle emissions (Huo et al., 2011). Therefore, to better capture city-specific unobserved factors that may affect daily air pollution, we control for both city fixed effects and city-specific time trends under the premise that the aggregate pollution trend across all cities does not jump discontinuously.
- Using the full panel data and global polynomial time trends up to the third order generates slightly larger estimates of the Notoll effect (Table A2).

Table 5
Results from city-specific time trend regressions.

Variable	1	2	3
Nationalday	−0.193***	−0.189***	−0.140***
	(−4.39)	(−3.80)	(−3.15)
Notoll	0.153***	0.217***	0.146**
	(3.17)	(3.48)	(2.14)
Asymmetric time trend	No	1st order	2nd order
Adjusted R^2	0.420	0.500	0.534
AIC	1785	814	169

Note: Dependent variable is log(API). All models also include weather variables, a month dummy, year dummy, weekend dummy, and city fixed effects. Column 2 includes linear time trend before, during, and after the "no toll" period and their interactions with city fixed effects. Column 3 includes linear and quadratic time trends before, during, and after the "no toll" period and their interactions with city fixed effects. The sample includes only seven days before, during, and after the National Day holiday for 2011 and eight days before, during, and after the National Day holiday for 2012. t statistics are in the parentheses. Standard errors are clustered at the province level. AIC denotes the statistics for Akaike's information criterion. Superscripts "*" indicate significance at the 10% levels, respectively. Sample size: 4410.

** Superscripts indicate significance at the 5% levels, respectively.

*** Superscripts indicate significance at the 1% levels, respectively.

Table A2
Results from panel data regressions with city-specific time trend.

Variable	1	2	3	4
Nationalday	−0.246***	−0.238***	−0.222***	−0.213***
	(−5.67)	(−5.69)	(−5.37)	(−5.12)
Notoll	0.232***	0.227***	0.212***	0.235***
	(3.92)	(3.73)	(3.41)	(3.51)
Asymmetric time trend	No	1st order	2nd order	3rd order
Adjusted R^2	0.372	0.394	0.407	0.423
AIC	37,463	34,705	32,822	30,620

1.3 PM_{10} and visibility results

Table 6
PM_{10} and visibility results.

Variable	1	2	3
Panel 1: Dependent variable: log(PM_{10})			
Nationalday	−0.251***	−0.252***	−0.221***
	(−4.39)	(−4.19)	(−3.85)
Notoll	0.197***	0.264***	0.213***
	(3.04)	(3.47)	(2.58)
Asymmetric time trend	No	1st order	2nd order
Adjusted R^2	0.421	0.428	0.430
AIC	4365	4318	4305
Sample size	4410		
Panel 2: Dependent variable: log(visibility)			
Nationalday	0.166***	0.183***	0.173***
	(3.74)	(3.73)	(2.85)
Notoll	−0.092**	−0.102*	−0.086
	(−2.18)	(−1.90)	(−0.95)
Asymmetric time trend	No	1st order	2nd order
Adjusted R^2	0.719	0.720	0.720
AIC	3670	3648	3653
Sample size	4355		

Table A3

PM_{10} and visibility results using global polynomial time trends.

Variable	1	2	3	4	5
	Panel 1: Dependent variable: $\log(PM_{10})$				
Nationalday	−0.318***	−0.304***	−0.280***	−0.270***	−0.253***
	(−5.86)	(−5.77)	(−5.38)	(−5.05)	(−5.30)
Notoll	0.301***	0.288***	0.254***	0.270***	0.249***
	(3.96)	(3.74)	(3.25)	(3.17)	(3.19)
Asymmetric time trend	No	1st order	2nd order	3rd order	4th order
Adjusted R^2	0.366	0.366	0.367	0.367	0.368
AIC	80,187	80,123	80,021	80,003	79,913
Sample size	70,400				
	Panel 2: Dependent variable: log(visibility)				
Nationalday	0.135***	0.133***	0.143***	0.138***	0.119***
	(4.48)	(4.46)	(4.72)	(4.23)	(3.81)
Notoll	−0.103**	−0.057	−0.113***	−0.101**	−0.085*
	(−2.39)	(−1.41)	(−2.68)	(−2.12)	(−1.68)
Asymmetric time trend	No	1st order	2nd order	3rd order	4th order
Adjusted R^2	0.690	0.690	0.690	0.690	0.691
AIC	69,022	69,023	68,991	68,976	68,909
Sample size	69,534				

1.4 Testing the intertemporal shift of travel demand

- Although the city-specific time trend models provide compelling evidence that eliminating tolls significantly increases air pollution, this effect may be overestimated if trips originally scheduled shortly after the National Day holiday simply shifted forward to the holiday period when tolls were waived. This intertemporal displacement effect is termed the “harvesting effect”.
- To test this harvesting effect, we add a dummy variable set to one if a day is one of the eight days right after the “no toll” policy period and re-estimate Model (1).
- Since the control group now is days outside of the narrow window, we use the full sample and global high-order polynomial regressions.

Table 7
Testing the intertemporal shift of travel demand.

Variable	1	2	3	4	5
Panel 1					
Nationalday	−0.239***	−0.226***	−0.213***	−0.206***	−0.198***
	(−5.94)	(−5.84)	(−5.57)	(−5.28)	(−5.45)
Notoll	0.232***	0.223***	0.202***	0.214***	0.195***
	(3.91)	(3.72)	(3.30)	(3.16)	(3.06)
Eight days after no toll	0.047	0.064	0.042	0.035	0.003
	(1.20)	(1.56)	(1.10)	(0.89)	(0.07)
Asymmetric time trend	No	1st order	2nd order	3rd order	4th order
Adjusted R^2	0.372	0.373	0.374	0.374	0.375
AIC	37,450	37,376	37,296	37,280	37,193
Panel 2					
Nationalday	−0.240***	−0.228***	−0.216***	−0.208***	−0.199***
	(−5.96)	(−5.90)	(−5.65)	(−5.34)	(−5.50)
Notoll	0.236***	0.231***	0.217***	0.238***	0.212***
	(3.96)	(3.85)	(3.52)	(3.44)	(3.22)
Eight days before no toll	0.092***	0.089***	0.070***	0.072***	0.034
	(5.48)	(5.38)	(3.57)	(3.82)	(1.53)
Eight days after no toll	0.049	0.064	0.046	0.046	0.011
	(1.23)	(1.56)	(1.19)	(1.15)	(0.29)
Asymmetric time trend	No	1st order	2nd order	3rd order	4th order
Adjusted R^2	0.373	0.374	0.374	0.374	0.375
AIC	37,395	37,326	37,268	37,250	37,189

1.5 Placebo test and sensitivity test

- Our identification strategy relies on the assumption that the National Day holiday in 2011 serves as a good comparison to help isolate the holiday effect from the toll waiver effect for the National Day holiday in 2012. However, if the National Day holiday in 2011 has an unobserved, upward trend in air pollution which is not controlled for by flexible time trends, then such an upward trend will confound our "Notoll" policy variable and therefore the toll waiver effect will be overestimated.
- To test whether the National Day holiday in 2011 serves as a good control group, we do two placebo tests. The first test uses the data for year 2009 and 2010 and assumes that tolls were waived during the 2010 National Day holiday period. Similarly, the second test combines the data for year 2010 and 2011 and assumes that tolls were waived during the 2011 National Day holiday period.

Table 8
Placebo test and sensitivity test.

Variable	1	2	3
Panel 1: Real data			
Nationalday	−0.193***	−0.193***	−0.170***
	(−4.39)	(−4.26)	(−4.04)
Notoll	0.153***	0.201***	0.164***
	(3.07)	(3.42)	(2.78)
Adjusted R^2	0.420	0.427	0.428
AIC	1785	1736	1725
Sample size	4410	4410	4410
Panel 2: Assume 2010 had a toll waiver, 2009 as comparison			
Nationalday	−0.147***	−0.169***	−0.110***
	(−4.89)	(−4.83)	(−3.46)
Notoll	0.088***	−0.062	−0.067
	(4.48)	(−1.23)	(−0.89)
Adjusted R^2	0.417	0.427	0.437
AIC	847	793	734
Sample size	3375	3375	3375
Panel 3: Assume 2011 had a toll waiver, 2010 as comparison			
Nationalday	−0.045	−0.125**	−0.117**
	(−1.37)	(−2.59)	(−2.53)
Notoll	−0.119**	−0.397***	−0.225***
	(2.05)	(−4.62)	(−3.55)
Adjusted R^2	0.446	0.475	0.480
AIC	1512	1325	1289
Sample size	3633	3633	3633
Panel 4: Sample of 2009, 2010, 2011, and 2012 data			
Nationalday	−0.149***	−0.120***	−0.104**
	(−6.09)	(−4.42)	(−3.36)
Notoll	0.111**	0.125***	0.165***
	(4.30)	(3.46)	(3.04)
Adjusted R^2	0.391	0.394	0.397
AIC	3087	3051	3013
Sample size	7785	7785	7785

1.6 Estimating the toll elasticity of pollution

- To be more informative, we replace the Notoll dummy by the weighted toll rate in each city to estimate the toll elasticity of pollution. We manually collect the toll rate of each highway in each city, then use the length of each highway as a weight to compute the weighted average of highway toll for each city.
- Table 9 reports the results of panel data models with a narrow window where the Notoll dummy is replaced by a weighted toll rate in each city.
- Using global polynomial time trends with the full panel data set generates similar results (Table A4).

Table 9
Toll elasticity of pollution.

Variable	1	2	3
Nationalday	-0.182^{***}	-0.173^{***}	-0.153^{***}
	(−4.59)	(−4.31)	(−4.10)
Weighted toll rate	-0.321^{***}	-0.369^{***}	-0.266^{**}
	(−3.38)	(−3.44)	(−2.18)
Asymmetric time trend	No	1st order	2nd order
Adjusted R^2	0.420	0.426	0.428
AIC	1787	1743	1728

Table A4

Toll elasticity of pollution using global polynomial time trends.

Variable	1	2	3	4	5
Nationalday	−0.230***	−0.223***	−0.209***	−0.200***	−0.188***
	(−5.67)	(−5.65)	(−5.40)	(−5.04)	(−5.13)
Weighted toll rate	−0.490***	−0.425***	−0.352**	−0.347**	−0.313*
	(−4.22)	(−3.37)	(−2.45)	(−2.07)	(−1.87)
Asymmetric time trend	No	1st order	2nd order	3rd order	4th order
Adjusted R^2	0.372	0.373	0.374	0.374	0.375
AIC	37,479	37,412	37,322	37,291	37,195

Conclusions

- Vehicles generate congestion and pollution externalities. A toll can be charged to alleviate congestion and reduce vehicle emissions. In the absence of a toll the number of vehicles on the road will exceed the optimal number that maximizes social welfare.
- When highway tolls were waived nationwide for passenger vehicles during the 2012 eight-day National Day holiday period, urban air pollution increased by about 20%; PM_{10} increased by 26%; and visibility decreased by one kilometer.
- The findings suggest that the policy of eliminating tolls during holidays generates a significant loss of social welfare.

- Although due to data availability we are unable to quantify how much the optimal toll should be during the national holidays, this study does provide the first empirical evidence on the effect of road pricing on air pollution in China; it also complements the scant literature on empirical studies of the environmental effect of road pricing.
- The study provides a timely and useful reference to the policymakers of those cities.

Thanks!