Evaluating Urban Transportation Policies

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Traffic congestion poses a significant challenge in urban centers especially in fast-growing emerging economies where rapid urbanization and the increase in travel demand have outpaced road infrastructure and regulations. Longer travel times and worsened air quality resulting from traffic congestion hinder mobility and urban development while reducing the overall quality of life in urban areas. According to the 2018 TomTom Traffic Index that is based on real-time GPS traffic data in 403 cities from 56 countries, the ten most congested cities were all from developing and emerging economies where commuters spend over 200 hours of extra travel time per year relative to the free flow speed. Local governments have implemented a range of policies to address traffic congestion, targeting both the demand and supply sides of road infrastructure. On the demand side, policies encompass command-and-control style driving restrictions and vehicle purchase quota system, and market-based congestion pricing. On the supply side, efforts have been made to expand public transit options, such as buses and subways, and enhance road capacity.

This summary describes our research agenda in understanding the impacts of various urban transportation policies aimed at alleviating traffic congestion and air pollution. The research effort centers on measuring crucial empirical objects, including the marginal external cost of traffic congestion, and evaluating different policies in terms of both efficiency and equity within an integrated framework. Much of our analysis focuses on Beijing. With a population of over 21 million, the city has consistently ranked among the most congested in the world. Its municipal government has implemented aggressive demand-side and supply-side policies over the past 15 years, making it an ideal setting for studying urban transportation policies.

Estimating the Marginal External Cost of Traffic Congestion

Economic theory indicates that the optimal congestion charge is equal to the marginal external cost of congestion (MECC) at the socially optimal level of traffic. The MECC critically hinges on the incremental effect of traffic density on traffic speed, i.e., how much an additional vehicle on the road slows down the traffic. Empirical estimation of the density-speed relationship is subject to the endogeneity challenge, as speed and density affect each other and both are equilibrium outcomes influenced by idiosyncrasies. Our study provided to our knowledge the first causal estimate of the density-speed relationship by leveraging plausibly exogenous variations in traffic introduced by Beijing's driving restriction policy. [1]

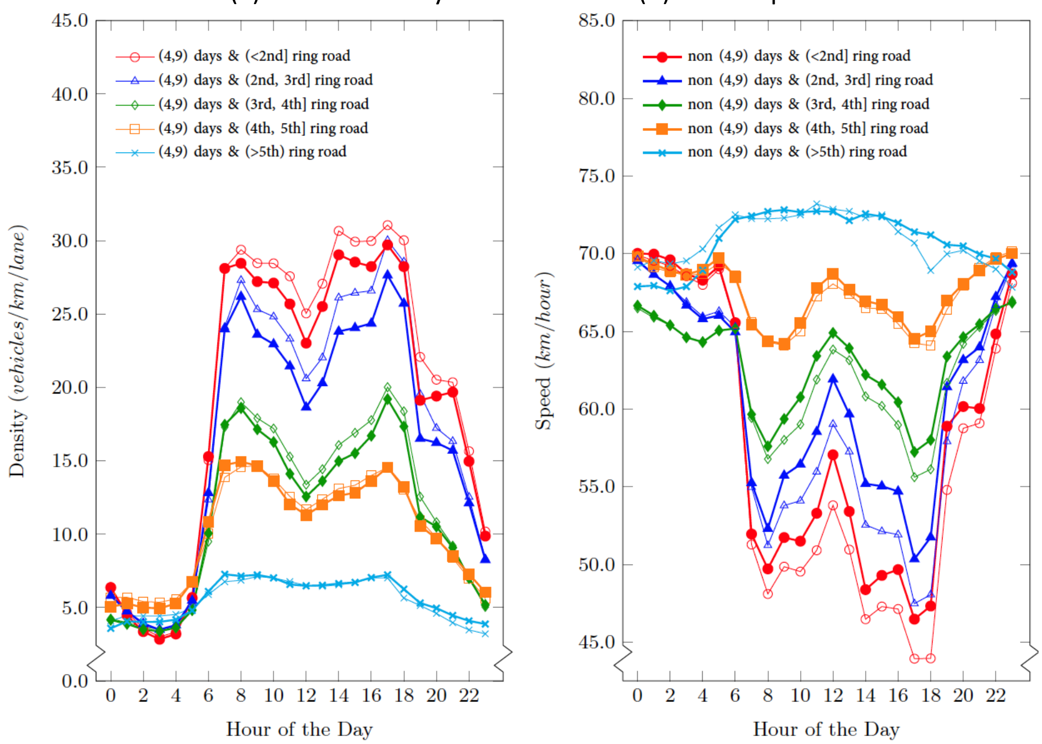
Beijing's driving restriction policy prohibits certain vehicles from driving within the 5th ring road from 7am to 8pm during workdays. It follows a predetermined rotation schedule based on the

[1] "The Marginal Cost of Traffic Congestion and Road Pricing: Evidence from a Natural Experiment in Beijing," Yang J, Purevjav A, and Li S, *American Economic Journal: Economic Policy*, 12 (1), 2020, pp. 418-53.

last digit of a vehicle's license plate, restricting different pairs of numbers on different days (one and six, two and seven, three and eight, four and nine, or five and zero). Due to the non-uniform distribution of the last digit of license plate numbers, the policy exogenously shifts the number of vehicles on the road. Notably, vehicles with license plates ending in the number '4' constitute only about 2 percent of all vehicles due to the Chinese cultural aversion to the number four. Consequently, on days when vehicles with license plates ending in 4 and 9 are restricted, there are more vehicles on the road, leading to heightened congestion compared to other days. This variation in traffic speed and density as shown in Figure 1 is used to establish the causal relationship between traffic speed and density.

Figure 1: Traffic Density and Speed by Location and Hour of the Day

(a) Traffic Density (b) Traffic Speed



Note: The plots compare the hourly variation of average traffic density in Panel (a) and average vehicle speed in Panel (b) between weekdays when license plates ending in (4, 9) are restricted and other weekdays for different ring-road locations denoted by each line. Source: Yang J, Purevjav A, and Li S, "The Marginal Cost of Traffic Congestion and Road Pricing: Evidence from a Natural Experiment in Beijing," *American Economic Journal: Economic Policy*, 12 (1), 2020, pp. 418-53.

Our analysis, utilizing hourly traffic data for a year from about 1500 monitors in Beijing, reveals that addressing endogeneity in the relationship between speed and density results in a 60% increase in the estimate of the marginal cost of congestion compared to that obtained through OLS. Therefore, relying on OLS estimates would induce a significant downward bias in optimal congestion charges. Additionally, the marginal cost of congestion exhibits notable heterogeneity over time and particularly across different locations. Our analysis demonstrates that implementing time-varying and location-specific congestion charges could lead to substantial congestion reduction, welfare gains, and government revenue.

A Unified Framework for Policy Comparison

A large literature, including our own studies, has examined the effects of various transportation policies on outcomes such as vehicle ownership, travel mode choices, traffic congestion, air pollution, housing prices, and job access. On vehicle quota systems, our analysis suggests that while the lottery system is more equitable and effective in reducing automobile externalities than auctions, the advantage is offset by a significant allocative cost from misallocation.[2] Using the opening of 14 new subway lines during 2008-2016 in Beijing, we showed that subway expansions improved air quality, but the resulting health benefit is small relative to the construction and operating costs. Hence, the cost of subway expansion needs to be justified by traffic congestion relief and other economy-wide impacts.[3] In terms of driving restrictions, the policy in Beijing steepened the housing bid-rent curve, led to a higher premium for properties closer to subway stations, and changed the spatial distribution of households around subway lines.[4]

However, empirical studies that evaluate and compare different policies within a unified framework are lacking. To address this significant gap in the literature, we have developed an equilibrium model of residential sorting that allows us to compare the efficiency and equity impacts of various transportation policies within one unified framework.[5]

In the model, households choose a residence given the job locations of the working members. A key consideration in a household's choice of a residential property is its ease of commute for each working member of the household. The ease-of-commute measure is derived from a model of travel mode choices and is an equilibrium object that crucially depends on traffic congestion, which varies across locations and results from all households' travel choices and residential locations. Our explicit modeling of the travel mode choices to derive the ease-of-commute measure provide a micro-foundation for the linkage of the housing market and the transportation sector. This modeling choice represents an important departure from the literature which typically use the distance to the central business district to capture the ease of commute without endogenizing congestion.

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[2] "Better Lucky Than Rich? Welfare Analysis of Automobile Licence Allocations in Beijing and Shanghai," Li S, *The Review of Economic Studies*, 85(4), October 2018, pp. 2389–2428.

[3] "Does subway expansion improve air quality?" Li. S, Liu Y, Purevjav A, and Yang L, *Journal of Environmental Economics and Management*, 96(C), 2019, pp. 213-235.

[4] "The Impact of Road Rationing on Housing Demand and Sorting," Jerch R, Barwick P, Li S and Wu J. , SSRN Working paper, 2021. Available at http://dx.doi.org/10.2139/ssrn.3766254.

[5] "Efficiency and Equity Impacts of Urban Transportation Policies with Equilibrium Sorting," Barwick P, Li S, Waxman A, Wu J, and Xia T. NBER working paper 29012, 2022.

In the housing market, choices of individual households aggregate to total housing demand, and housing prices adjust to equate demand and supply. In the transportation sector, the equilibrium congestion level and hence driving speed is jointly determined by driving demand through all individuals' travel mode choices and road capacity. These two markets interact in two dimensions: The spatial locations of households affect the distance of work commutes and the choice of travel mode, hence congestion and driving speeds in the transportation sector. At the same time, the level of traffic congestion in the transportation sector affects the attractiveness of residential locations through the ease-of-commute utility as discussed above, which, in turn, shapes the spatial distribution of households.

The model premises include two sets of preferences that govern household choices: (1) preference parameters for housing attributes including the ease-of-commute measure, and (2) preference parameters for travel mode attributes such as travel time and travel cost. With these underlying parameters estimated, the model allows us to conduct counterfactual simulations to predict new equilibrium outcomes under different policy scenarios in terms of travel mode choices, household locations, the congestion level, housing prices, and welfare consequences.

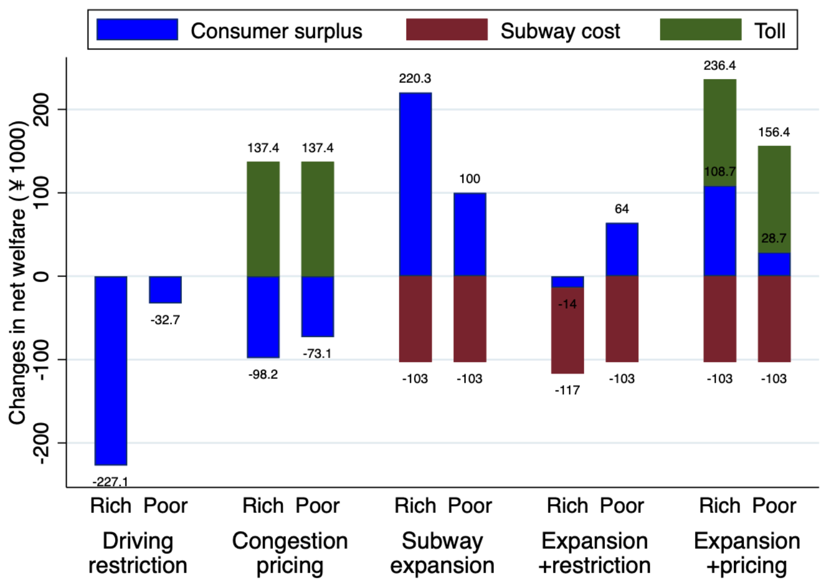
We rely on two rich datasets for estimation. The first dataset is the Beijing Household Travel Survey, a large representative survey that records households' home and work locations, trips made in a 24-hour window, and other demographic and transportation-related information. Based on API requests from online mapping service and GIS software, we compile the commuting route, distance, travel time, and pecuniary travel cost for each travel mode of all home-to-work trips. The second dataset contains housing transactions from a major government-run mortgage program and provides a large representative sample of Beijing home buyers. Critically for our analysis, the housing data report not only the home location but also the work locations of both household members. We then construct over 13 million hypothetical work-commute and travel-mode combinations for all properties in each home buyer's choice set, using the same procedure as in the travel survey.

Our estimation follows a two-step procedure. The first step recovers heterogeneous preferences on travel times and monetary costs (and thereby the value of time) based on the travel data. We then utilize the estimated parameters from this step and household members' work locations to construct the ease-of-commute measure separately for each commuter in the household and for all properties in a household's choice set. These variables are included as household property-specific attributes in the housing demand estimation in the second step. Based on the housing transaction data, the second step of our estimation recovers preferences for housing attributes including the preference for the ease-of-commute.

We simulate equilibrium residential sorting and transportation outcomes under different policies: driving restrictions, subway expansion, distance-based congestion pricing, as well as combinations of the three (subway expansion plus driving restrictions, and subway expansion plus congestion pricing). To facilitate comparison, the congestion charge is chosen to achieve the same level of congestion reduction as driving restrictions though our model also yields estimates of the optimal congestion charge.

Our policy simulations provide four important findings. First, different transportation policies exhibit distinct efficiency properties (Figure 2). While driving restrictions and congestion pricing achieve the same level of congestion reduction by design, congestion pricing improves welfare but driving restrictions reduces welfare due to the large distortion in travel mode choices. Beijing's rapid subway expansion increased aggregate welfare, despite the fact that it achieved only a modest congestion reduction. Congestion pricing and subway expansion in tandem deliver the largest improvement to traffic speed and net welfare gain—equivalent to 3% of average household income. In addition, the revenue from congestion pricing could fully finance the capital and operating costs of subway expansion, eliminating the need to resort to distortionary taxes to fund the infrastructure investment.

Figure 2: Per Capita Welfare Impacts of Different Policies



Notes: Each bar denotes changes in net welfare per capita relative to the baseline scenario of no policy under the 2008 subway network, separately for rich households (household income above the median) and poor households (household income below the median). The congestion pricing is a distance-based charge (at Yuan 1.13/km) and achieves the same level of congestion reduction as that from driving restrictions. The subway expansion simulation compares the subway networks in 2008 and 2014. **Source:** Barwick P, Li S, Waxman A, Wu J, and Xia T. Efficiency and Equity Impacts of Urban Transportation Policies with Equilibrium Sorting, 2022. NBER working paper 29012.

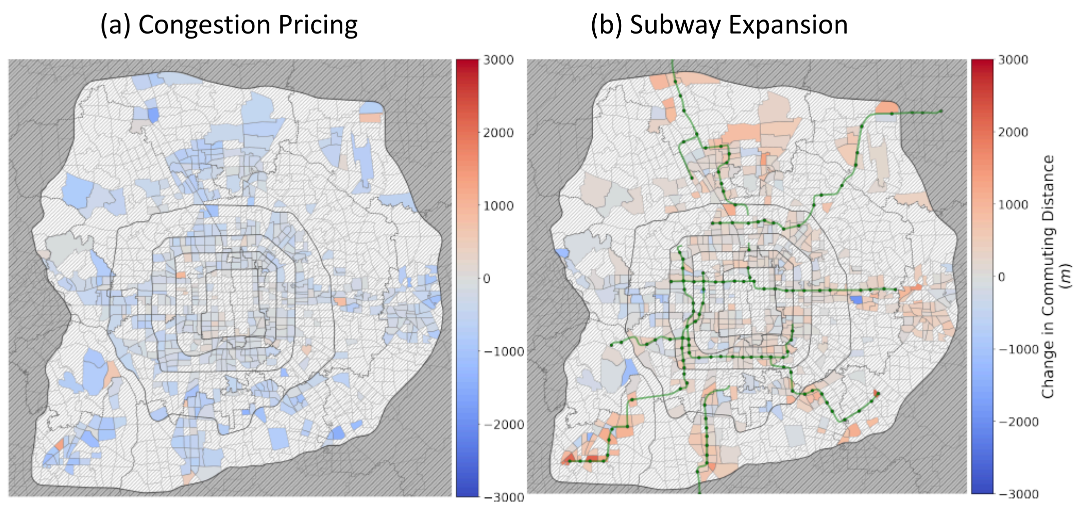
Second, different policies exhibit notable disparities in terms of distributional consequences. Without revenue recycling, congestion pricing is regressive, posing a substantial obstacle to its practical implementation. In contrast, driving restrictions and particularly subway expansion are progressive, which likely contributes to their greater adoption in practice. However, it is worth noting that with appropriate revenue recycling, congestion pricing can be welfare enhancing for low-income households, thereby addressing distributional concerns.

Third, although all three policies help alleviate congestion, they have distinct and even contrasting effects on the spatial distribution of residential areas and equilibrium housing prices

(Figure 3). Distance-based congestion pricing creates strong incentives for both high- and low-income commuters to relocate closer to their workplaces. In contrast, subway expansion increases the spatial separation between residential and job locations by dispersing households from the city center toward suburban areas and locations near new subway stations.

Finally, residential sorting can either bolster or undermine the effectiveness of transportation policies aimed at reducing congestion. Sorting reinforces the efficiency of congestion pricing as households, particularly those with lengthy commutes, are motivated to reside closer to their workplaces and reduce driving. This amplifies the welfare benefits of congestion pricing especially for the high-income households. Conversely, sorting in response to subway expansion results in increased spatial separation between residential and work areas, diminishing both the congestion-reduction effect and welfare gains derived from infrastructure investment.

Figure 3: Changes in Work Commute Distance



Notes: Figures depict changes in the distance to work under congestion pricing in Panel (a) and subway expansion in Panel (b) relative to the baseline of no policy for households in each Traffic Administration Zone (denoted by gray lines) within the 6th ring road of Beijing. **Source:** Barwick P, Li S, Waxman A, Wu J, and Xia T. Efficiency and Equity Impacts of Urban Transportation Policies with Equilibrium Sorting, 2022. NBER working paper 29012.

Additional simulations reveal that the aggregate welfare implications vary qualitatively depending on whether we endogenize traffic congestion or not in our model. Moreover, excluding preference heterogeneity yields welfare estimates that differ by several folds. These findings underscore the advantages of our equilibrium sorting model in capturing diverse adjustment mechanisms and assessing different policies within a unified framework that accounts for general equilibrium effects and preference heterogeneity.

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