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The effect of vehicle ownership restrictions on travel behavior: Evidence from the Beijing license plate lottery[☆]

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ABSTRACT

To combat traffic congestion and air pollution, many cities restrict vehicle ownership, but little is known about how these policies actually affect vehicle ownership, use, or travel time. Leveraging the randomization created by Beijing's vehicle license plate lottery, we estimate the effects of the policy on travel behavior. We find that the policy reduces the total stock of cars in Beijing by 14%. It also causes large reductions in vehicle distance traveled, morning rush hour driving, and evening rush hour driving.

1. Introduction

Cars are a major contributor to some of the most important environmental issues today: air pollution, congestion, and climate change. Much of the future growth in cars is expected to occur in the developing world. Demand for petroleum in non-OECD countries has passed that of OECD nations, and is expected to grow a further 60% by 2030 (EIA, 2015).

Despite the large negative externalities associated with cars, policy makers have struggled to formulate an effective response. Road space rationing, where cars with selected license plates are fined if they drive on certain days during peak congestion hours, has been deployed in large cities such as México City, Santiago, and São Paulo. Davis (2008) concludes that driving restrictions have little effect on vehicle use, air pollution, and congestion in México City. Wang et al. (2013) find that almost half of drivers evaded Beijing's vehicle use restrictions. Even so, Viard and Fu (2015) find that the Beijing vehicle use restrictions result in some air quality improvements, and Zhong et al. (2017) find that they reduce ambulance calls and reports of heart-related symptoms. Overall, these studies highlight a key problem with road space rationing: evasion of these policies is widespread, diminishing their effectiveness.

In this paper, we study a second type of policy response that an increasing number of cities are undertaking: restrictions on vehicle ownership. In cities like Singapore, Beijing, and Shanghai, potential car buyers cannot freely add cars to their households, but must first bid in an auction or win a lottery for the right to purchase a car. As of 2017, eight Chinese cities with a combined

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population of more than 165 million restrict vehicle ownership. Many additional cities are considering similar policies (Yang et al., 2014). Vehicle ownership restrictions may be more effective than road space rationing because evasion is more difficult: one would have to purchase a car with a license plate from another area and be subject to the constant threat of fines. However, fines have not deterred those evading road space rationing, and no prior study has examined whether vehicle ownership restrictions are actually effective.

We perform the first evaluation of the effectiveness of vehicle ownership restrictions at reducing vehicle ownership and vehicle use. Our setting is the Beijing vehicle license plate lottery, which began in 2011 and reduced new car sales by roughly three-fourths in its first year compared to the previous year. The lottery includes a randomized drawing that allows us to overcome the problems of confounders that usually apply to analysis of car ownership. Our paper sheds light on vehicle policies in China, one of the most important car markets and the top contributor worldwide to greenhouse gas emissions. In contrast to the mixed performance of road space rationing, we find unambiguous effects of vehicle ownership restrictions: they sharply cut car ownership and the amount of driving.

A major hurdle to analyzing ownership restrictions is that vehicle ownership is surely endogenous; many unobserved characteristics influence both car ownership and travel behavior.[1] Unobserved individual and household characteristics are likely to be a particularly salient problem when investigating the relationship between vehicle ownership and travel behavior. For example, because cars are often used for commuting, unobserved job opportunities or preferences over modes of transportation may bias attempts to compare households based on the number of cars they own. However, in the Beijing lottery, conditional upon entering, winning the lottery is randomly assigned and is therefore exogenous to all other characteristics of the household. As a result, we can evaluate the effects of the policy by comparing car ownership and travel behavior across winners and losers. Moreover, lottery status represents a natural instrumental variable (IV) for vehicle ownership, allowing us to estimate the effects of vehicle ownership on travel behavior.

We first show that lottery outcomes are uncorrelated with determinants of travel behavior, supporting the validity of the empirical strategy. While we cannot directly compare unobservable individual-level attributes, we confirm that observable household and individual attributes that should not be affected by the lottery, such as gender and birth year, are statistically indistinguishable across lottery winners and losers. Furthermore, winning the lottery is a strong predictor of car ownership, reducing concerns about weak instruments bias.

Then, we estimate the reduced-form effects of winning the lottery on vehicle ownership and travel. On average, winning the lottery increases the probability that a household has at least one car by 42 percentage points. Winning the lottery more than doubles total distance driven and the probability that the individual drives during the morning or evening rush hours.

In addition to the reduced-form effects of winning the lottery on car ownership and travel behavior, we estimate the effects of car ownership on travel behavior. This analysis provides insight into the potential effects on travel behavior of other policies that may affect ownership. To address the endogeneity of ownership, we use the lottery outcome to instrument for the number of vehicles owned by the households. Consistent with the reduced-form estimates, we find that reducing the number of household cars sharply cuts kilometers traveled–both overall and during rush hour times.

Finally, we use the reduced-form results to estimate the aggregate effects of the lottery on vehicle ownership and travel. These should be considered partial equilibrium estimates, in that they hold fixed congestion levels (and other factors that may affect vehicle ownership and use) at the levels observed during the lottery. Between 2011 and 2014, these restrictions decreased the total stock of cars in Beijing by 14%, a large amount.[2] Moreover, removing the lottery would increase total VKT in Beijing by 15%. Similarly, morning and evening rush hour car use would increase by 10%, implying that vehicle ownership restrictions have caused large decreases in congestion. Although we do not observe vehicle emissions, lower VKT implies substantial reductions in emissions of local air pollutants and greenhouse gases.

These conclusions have important implications for localities considering vehicle ownership restriction policies. In combination, our findings suggest that these policies are very effective at decreasing the number of cars owned and total distance driven. These changes also would be accompanied by substantial reductions in congestion, fuel consumption, and pollution emissions. In cities such as Beijing, with well-developed public transportation systems, our results also imply that limiting the expansion of vehicle ownership does not significantly increase overall commute distances.

The decrease in driving caused by the ownership restrictions implies substantial environmental benefits. However, we note that policies restricting vehicle ownership may still be economically inefficient. External costs of driving clearly vary across space and time, with travel in central areas of cities and during rush hours imposing higher costs. Pricing congestion and emissions would be more efficient because they restrict driving in proportion to external costs. In complementary work using the same data (Liu et al., 2018a, 2018b), we find that the Beijing lottery had unintended consequences, reducing fertility rates and female employment. Moreover, lotteries themselves may be allocatively inefficient compared with auctions, as demonstrated by Li (2019). Notwithstanding these inefficiencies, our analysis shows that Beijing's vehicle ownership restrictions have unambiguously reduced vehicles owned and distance driven, standing in stark contrast to the effects of vehicle usage restrictions.

[1] Raphael and Rice (2002) and Ong (2002) attempt to overcome this endogeneity by instrumenting for car ownership using variables such as state-level insurance premiums, gasoline taxes, and population density. These instruments may remove endogeneity concerns at the individual level, but are still open to endogeneity concerns at the level of the locality, since states with households that favor driving may enact favorable policies. A number of studies simultaneously model vehicle ownership and use (e.g., West, 2004; Bento et al., 2009), but these cannot overcome the problem of unobserved confounders.

[2] Our estimates on the effect of Beijing's ownership restrictions are about 27 percent larger than the reduction estimated by Yang et al. (2014). This is due primarily to differences in methodology: they use simple extrapolations, while we use natural experiment-driven variation in vehicle ownership.

2. Background, data, and randomization tests

2.1. Background

This subsection provides an overview of the lottery system. It draws many of the institutional details from Yang et al. (2014), who describe the background of the lottery. Beijing began its license plate lottery in January 2011. Without a Beijing license plate, cars are prohibited from driving within the area encircled by the fifth ring road between the hours of 7:00 a.m. and 9:00 a.m., and 5:00 p.m. and 8:00 p.m.[3] Those who already had cars were allowed to keep their vehicles and were allowed to retain their license plates when they traded in or upgraded their old cars. However, no household was able to add to its number of cars without first winning the lottery.[4]

From its inception, the lottery has aimed to reduce new car purchases. In its first months, applicants competed for one of 20,000 new license plates issued each month. To put this figure in perspective, annual new car sales grew at an average rate of 31% between 2001 and 2010 in Beijing, and reached a height of averaging 76,000 cars per month during 2010. During the first drawing, there were 10 times as many lottery applicants as license plates available, and the ratio of license plates offered in the lottery to the number of applicants has continued to drop as the number of license plates drawn remained constant and the pool of applicants swelled. By mid-2012, the probability of winning the lottery in a given month fell to less than 2%, and the success rate fell below 1% in 2015.

Officially, license plates won through the lottery adhere to the individual and cannot be transferred. However, there is anecdotal evidence that people lend their cars to relatives and friends for long periods of time; in these cases ownership technically resides with the lottery winner, but all benefits from usage exist with the person actually driving the car. As noted above, this issue should not cause misreporting on the survey and therefore should not affect the internal validity of our analysis because of the randomization of the lottery; the comparison of winners and losers yields unbiased estimates of the differing car ownership and travel behavior across the two groups. For the IV estimation, both the relevance and validity conditions are still satisfied for the instrument of the vehicle lottery. These kinds of effects can reduce the power of the instrument, but we do not find evidence of substantial weak instruments bias.

Despite the difficulty of obtaining a new car in Beijing, not all lottery winners purchase vehicles. Because entering the lottery is free and requires only an online website application, many households enter the lottery even if they are not sure that they want to purchase a car. For example, in June 2012, 10.9% of individual lottery winners did not purchase a car, and 22.8% of corporate lottery winners did not purchase a vehicle. This suggests that winning the lottery increases the average number of household vehicles by less than one.

2.2. Data

We leverage a large randomized survey on the transportation behavior of Beijing's residents. This survey is conducted every few years by the Beijing Transportation Research Commission (BTRC), a government agency tasked with understanding and improving Beijing's transportation system. The survey consists of 40,000 households, drawn randomly from a complete list of Beijing households, with the samples proportional to the population for each of Beijing's 16 districts. It was conducted between September and November 2014.[5]

The base survey consists of three types of questions. First, it asks about individuals in the household, including their genders, ages, and relationships with the head of household. Second, it asks about the household and its vehicles, including the numbers and types of vehicles in the household. The third set of questions, constituting the main dataset for this paper, asks household members to describe their travel for a 24-h period.

The travel diary starts by asking individuals where they began their day. A respondent reports the departure time from this starting point. Then, the travel diary queries the start and end locations of each leg of travel, the time of travel, the mode of travel, and the general purpose of that travel. For some people, the travel diary is as simple as taking the subway to work, and then returning home using the same route. For others, the travel diary is complex. For example, many Beijing residents commute to work using a combination of modes, such as a subway ride followed by a bus trip. They may go to the supermarket or to a restaurant; they may take a taxi or walk to a lunch destination. Each of these individual trips is recorded in the travel diary data.

At our request, the BTRC added to the 2014 survey questions about whether members in the household entered the Beijing car lottery. The survey asked which members entered and their dates of entry, as well as the dates the individuals won. If they won, the survey asked whether and when they purchased cars. About 20% of all households in the BTRC sample had at least one member participate in the lottery.

[3] We examine whether this set of rules causes lottery losers to evade these rules by purchasing cars and shifting car travel to non-peak hours. While lottery winners drive more than lottery losers during each hour of the day, both have approximately the same distribution of vehicle usage by hour of day, suggesting that this form of avoidance is not a major concern.

[4] As in other settings, cars may be driven into Beijing with license plates from other cities. However, cars without Beijing license plates are subject to the continuous threat of fines during restricted hours.

[5] It is unlikely that households would mis-represent on the survey the number of vehicles owned. The survey is conducted by a private firm (hired by the BTRC), and not by government officials. Additionally, there are no penalties for car ownership as long as the car is not driven during rush hours.

Table 1
Comparability of individuals entering and not entering the lottery.

	Entrants	Non-entrants	Difference
Female	0.4079	0.594	−0.187***
	(0.005)	(0.004)	(0.007)
Birth year	1975.794	1966.468	9.326***
	(0.126)	(0.144)	(0.198)
High school graduation rate	0.860	0.689	0.170***
	(0.004)	(0.004)	(0.006)
College graduation rate	0.625	0.406	0.218***
	(0.005)	(0.005)	(0.007)
N	10,589	8057	

$^{*}p < 0.10, ^{**}p < 0.05, ^{***}p < 0.01$.
This table compares the baseline characteristics of lottery entrants, who are all aged 18 and over, with the characteristics of non-entrants in our survey who were aged 18 and over.

Altogether, there were 40,005 households with 101,827 household members included in the BTRC survey. Among these households, 8066 individuals in 7039 households report entering the Beijing vehicle lottery. Table 1 shows that entrants differ from non-entrants in observable ways: entrants are less likely to be female, are younger, and are more highly educated.

2.3. Tests of randomization

Our empirical strategy relies on the random assignment of lottery status. To be more specific, conditional on date of entry, winning or losing the lottery is independent of all individual characteristics that might affect travel behavior.

To provide evidence supporting this condition, we examine whether winning and losing households are similar along observable dimensions that are determined prior to the lottery. Finding that observable characteristics are not correlated with lottery status would decrease the likelihood that unobserved characteristics are correlated with lottery status.

Among households with at least one entrant, we compare three sets of characteristics: those of the entrants themselves, those of the entrant's household head, and those of all household members. Table 2 presents these results, comparing gender composition, birth years, and education levels across winners and losers. In the table, the similarity between winners and losers would support the validity of the IV strategy using the sample of lottery entrants.

The left column of the table reports the mean and standard deviation of each characteristic for losers. To construct the right column, we regress the characteristic in the row heading on a dummy variable equal to one if the individual wins the lottery. Importantly, we condition on month of entry in this regression. These controls are necessary because early lottery entrants are more likely to obtain a car than later entrants. Earlier entrants not only had more lotteries in which they were entered, but also the Beijing lottery had higher success rates in early months. Moreover, members of households with stronger driving preferences may enter the lottery earlier than other households. Controlling for entry month implies that we are comparing lottery winners and losers who entered at the same time, controlling for potentially unobserved factors correlated with entry date.

Lottery entrants constitute the main estimation sample. For this sample, we do not observe large or statistically significant differences between winners and losers.

Household members of winners and those of losers differ slightly in their education levels, although not by statistically significant amounts. In Liu et al. (2018b), we explore differences in household composition between households of lottery winners and those of losers. We find that winning a car has a strong influence on the number of babies that lottery entrants choose to have, and the education differences may arise from the larger number of children in the households of winners.

We also examined the possibility of recall bias; because some survey respondents are surveyed three years after entering the lottery, they may not accurately remember their date of entry or whether they won the lottery. We conducted many informal interviews with lottery entrants, which confirmed the accuracy of their recollections. Obtaining a car seems important to households that want one, and entrants remember quite clearly the details surrounding their participation in the lottery.

As an additional test for recall bias, we segregated respondents by their reported entry year in Appendix Table 1. If recall bias affected the random assignment of winners and losers, we should observe differences in the characteristics of winners and losers that increase over time. We do observe some marginally statistically significant differences between winners and losers among our earliest entrants from 2011, but there is no evidence that these differences are larger in magnitude than the differences between winners and losers in later entry years. While we cannot rule out recall bias, the evidence suggests that this is not a serious problem.[6]

[6] Differences in some characteristics between treatment and control groups can arise purely out of chance. Even differences of statistical significance are fairly common in pure lotteries, such as those in Dobbie and Fryer (2011).

Table 2
Comparability of individuals winning and not winning the lottery for variables unaffected by the lottery.

	Losers (S.D.)	Coefficient (S.E.)
	Lottery Entrants	
Female	0.409	−0.004
	(0.492)	(0.019)
Birth year	1975.791	0.462
	(11.296)	(0.432)
High school graduation rate	0.861	−0.011
	(0.346)	(0.013)
College graduation rate	0.624	0.007
	(0.484)	(0.019)
N	7278	8057
	Heads of Household	
Female	0.489	0.000
	(0.500)	(0.019)
Birth year	1968.347	−0.198
	(12.003)	(0.460)
High school graduation rate	0.740	−0.011
	(0.438)	(0.017)
College graduation rate	0.466	−0.019
	(0.499)	(0.019)
N	7278	8057
	All Household Members	
Female	0.505	−0.002
	(0.178)	(0.007)
Birth year	1974.877	0.289
	(10.046)	(0.386)
High school graduation rate	0.715	−0.023**
	(0.288)	(0.011)
College graduation rate	0.473	−0.019
	(0.342)	(0.013)
N	7278	8057

$^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$.
This table includes only lottery entrants, reporting the means and standard deviations for lottery losers in the left column. The right column reports the results of a regression of the indicated variable on whether the entrant won the lottery, along with month-of-entry fixed effects. The top panel includes just the lottery entrants. The middle panel includes the characteristics of the household head for each entrant. The bottom panel includes the average of that household characteristic for each entrant.

3. Reduced-form estimates

Having provided evidence supporting the randomization of the lottery, we examine whether the lottery has affected vehicle ownership and use. We exploit the randomization to estimate the reduced-form effect of the lottery on these outcomes. A naive consideration of the lottery would suggest that average vehicle ownership of winners and losers should differ by one car, but in practice this difference may be less than one if some winners elect not to obtain an additional car or if some losers can circumvent the lottery and obtain an additional car without winning.

To estimate the reduced-form effect of vehicle ownership restrictions, we employ the following equation:

$$C_i = \beta_0 + \beta_1 W_i + \beta_2 X_i + \beta_3 \eta_i + \mu_i \qquad (1)$$

In this equation, C_i is the dependent variable in the household of individual i. The dependent variables include the number of cars in the household, whether the household has a car, the average age of vehicles in the household, average VKT per car, total fuel spending, average fuel cost per car in the household,[7] and distance and time traveled (overall and by mode).[8] Although these variables are measured at the household level, our analysis is conducted at the individual level. Lottery status is randomly assigned at the individual level, but is potentially endogenous at the household level since some households have more than one lottery entrant. Households with more than one entrant are likely to have greater demand for cars as well as greater demand

[7] The BTRC survey asks each household to report the age of the car and monthly spending on fuel. Because these variables are self-reported, responses are usually rounded approximations. For example, the most common response to this question was that spending on fuel was 1000 RMB.

[8] Ideally, we would be able to observe the distance traveled by observing the route selection of each person during each trip. Because this is not feasible, we estimate the daily distance traveled. First, we divide Beijing into approximately 1600 traffic zones defined by the survey administrators. Each traffic zone is about 1 square km. In the travel survey, the origin and destination of each trip are placed into a traffic zone in Beijing, and the straight-line distances between the centroids of the pairs of traffic zones are calculated. Because the size of the traffic zones is small, this imputation is likely to introduce only a small amount of measurement error. In addition, travel times are not affected by this source of measurement error.

Table 3
Reduced-form estimates of the effect of winning the lottery for key vehicle outcomes.

	Losers (S.D.)	Coefficient (S.E.)
	Relating to the Stock of Cars	
Number of cars	0.557	0.636***
	(0.613)	(0.021)
Has a car	0.495	0.421***
	(0.500)	(0.011)
Avg. vehicle age	4.061	−1.484***
	(1.827)	(0.079)
Avg. VKT per car	13,220	−2898***
	(13,105)	(608)
Fuel cost per household	474.5	415.084***
	(803.085)	(27.553)
Fuel cost per car	840.402	−118.468***
	(684.800)	(16.917)
	Relating to Travel by Car	
VKT - all	6.693	7.868***
	(18.960)	(1.169)
VKT - commute	2.255	2.895***
	(7.494)	(0.574)
Time of travel (minutes) - all purposes	18.607	20.307***
	(50.504)	(2.782)
Time of travel (minutes) - commute	10.799	10.817***
	(23.760)	(1.719)
Used car during morning rush hour	0.179	0.211***
	(0.449)	(0.022)
Used car during evening rush hour	0.146	0.183***
	(0.392)	(0.022)

$^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$.
This table includes only lottery entrants, reporting the means and standard deviations for lottery losers in the left column. The right column reports the results of a regression of the indicated variable on whether the entrant won the lottery, along with covariates from equation (1).

for travel. Moreover, as discussed in the previous section, the lottery outcome may affect household size, in which case it would not be appropriate to include variables related to household size as independent variables.

Among the independent variables, W_i is the lottery status of the individuals (whether they have won the lottery). The variable X_i is a vector of individual covariates not affected by the lottery, and we include age, gender, fixed effects for education group, and fixed effects for the day of travel in the diary.

As with the balance tests reported in the previous section, we include fixed effects for lottery month of entry, η_i. The coefficient β_1 is identified by within-entry month variation.[9]

Because the lottery outcome is randomly assigned, β_1 is the causal effect of winning the lottery on the number of cars in the household of individual *i*. The coefficient represents the change in the number of cars if a loser were given the right to obtain a car. We report the results for these regressions in Table 3.

We can see from this table that winning the lottery has a large and statistically significant effect both on the number of cars in the household and whether the household has a car. Winning the lottery increases the number of cars in the household by 0.636 cars, and increases the likelihood that the household has a car by 42.1 percentage points.[10] Winning the lottery roughly doubles the number of cars and VKT, indicating that VKT increases roughly in proportion to the number of cars.

We note several reasons that each lottery win increases the number of cars by less than one full car. First, not every lottery winner purchases a car. As we mentioned earlier, about 10% of lottery winners allow their rights to purchase cars to expire. Second, losers may find other mechanisms to obtain cars. The literature on road space rationing shows widespread evasion of the road use restrictions. There is anecdotal evidence that some evasion of vehicle ownership restrictions is also possible.[11] Our results suggest that, even accounting for efforts by lottery losers to obtain cars, vehicle ownership restrictions are effective because there is a large gap in vehicle ownership between lottery winners and losers.

Other characteristics of cars in the home offer supporting evidence that the lottery has a strong influence on the number of cars. The average age of cars of lottery winners is 1.5 years lower than of lottery losers, suggesting that winning households have

[9] Note that our fixed effects imply that the coefficient is unbiased even if the ownership restrictions caused individuals to enter the lottery who would have delayed purchasing a new car in the absence of the lottery. Such a "pull-forward" effect would not bias the estimates because the randomization of the lottery implies that the winning and losing households contain similar proportions of such households. Below, we estimate the magnitude of the pull-forward effect to extrapolate our results outside the lottery sample.

[10] We note that lottery entrants include people who entered between 2011 and 2014. Our estimate is therefore an average treatment effect over these years.

[11] In informal conversations with Beijing residents, we find that some individuals use cars that relatives and friends have won in the lottery. Yang et al. (2014) note that some individuals purchased license plates through car dealers who hoarded plates prior to the advent of the vehicle lottery.

Table 4
Reduced-form estimates of the effect of winning the lottery for overall travel outcomes.

	Losers (S.D.)	Coefficient (S.E.)
	Distance (km)	
All modes	23.457	2.298
	(26.820)	(1.489)
By car	6.693	7.868***
	(18.960)	(1.169)
By bus	8.364	−3.122***
	(18.933)	(0.637)
By subway	4.069	−1.731***
	(12.007)	(0.512)
By foot or bike	3.845	−0.529
	(8.603)	(0.556)
	Time (min)	
All modes	70.281	2.026
	(60.644)	(2.728)
By car	18.607	20.307***
	(50.504)	(2.782)
By bus	23.117	−9.707***
	(46.169)	(1.566)
By subway	7.347	−3.692***
	(24.202)	(0.793)
By foot or bike	20.168	−4.649***
	(36.606)	(1.319)

$^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$.
This table includes only lottery entrants, reporting the means and standard deviations for lottery losers in the left column. The right column reports the results of a regression of the indicated variable on whether the entrant won the lottery, along with covariates from equation (1).

newer vehicles. Households of lottery winners report spending more on gasoline than those of lottery losers. Lottery winners report lower average fuel costs per car; this occurs because new cars usually have higher fuel economy than old cars, and some winning households are adding second vehicles.

We investigate whether car ownership affects rush hour car use by defining two indicator variables, which are equal to one if the individual travels during the morning or evening rush hour periods. Based on typical hourly congestion levels observed in Beijing, we define the morning rush hour as weekdays between 7 and 10 a.m., and the evening rush hour as between 5 and 8 p.m. Winning the lottery more than doubles the probability that the individual uses a car during the morning or evening rush hour.

Table 4 reports estimates of equation (1) for which the dependent variable is the distance or time traveled by the mode indicated in the row heading. An individual's VKT includes all car travel, including cars belonging to the household or not, such as a ride from a friend or from a ridesharing service.[12] Winning the lottery does not affect total distance traveled by a statistically significant amount, but it does induce substantial substitution of distance traveled from bus and subway to cars. Winning the lottery reduces the time spent taking the bus, subway, or foot/bike, and increases time spent in a car. For each outcome, the effects of the lottery are large relative to the sample mean for losing individuals.

4. IV estimates on the effects of vehicle ownership restrictions

4.1. Effect on VKT and travel time

We next turn to estimating the effect of owning an additional car on distance traveled by car (i.e., VKT). Whereas the reduced-form results in the previous section quantify the effects of the lottery on car ownership and travel behavior, the IV estimates are useful for evaluating the effects on VKT of another policy that affects vehicle ownership. For example, if Beijing were to increase registration taxes, vehicle ownership might decrease and the IV results would enable an estimate of the change in VKT that would result from the decline in ownership.

A naïve approach might regress travel behavior outcomes on the number of household cars plus controls such as age and education:

$$Y_i = \gamma_0 + \gamma_1 Cars_i + X_i\gamma + \epsilon_i \quad (2)$$

[12] Travel by taxi or ridesharing services is relatively uncommon in our sample, accounting for a small share of total VKT.

Table 5
IV regressions on travel distance and time by car.

	All Travel		Commute	
	Distance (km)	Time (min)	Distance (km)	Time (min)
	Lottery Entrants			
Number of cars	12.194***	31.938***	5.774***	17.634***
	(1.611)	(4.364)	(1.031)	(2.536)
Age of member	−0.101***	−0.045	−0.045***	−0.095**
	(0.028)	(0.039)	(0.016)	(0.044)
Is female	−5.548***	−13.883***	−2.455***	−6.976***
	(0.713)	(1.350)	(0.455)	(1.093)
N	7015	8057	5556	4473
R^2	0.113	0.119	0.110	0.172
	Household Average			
Number of cars	7.799***	18.002***	4.159***	12.974***
	(0.868)	(1.824)	(0.572)	(1.731)
Age of member	−0.029*	0.099***	−0.008	0.072***
	(0.017)	(0.019)	(0.012)	(0.024)
Is female	−0.623	0.488	−0.061	0.930
	(0.461)	(0.711)	(0.246)	(0.584)
N	7015	8057	6342	6333
R^2	0.025	0.017	0.017	0.020

$^{*}p < 0.10, ^{**}p < 0.05, ^{***}p < 0.01$.
Regressions include only lottery entrants. All regressions include fixed effects for the day of the week of the interview, for the education level of the entrant, and for the month of entering the lottery. Standard errors are robust and clustered at the city district level.

where Y_i is the travel outcome, such as VKT, for individual i, $Cars_i$ is the number of cars in the household of individual i, X_i is a vector of other covariates, and ϵ_i is a random error term. The coefficient of interest is γ_1, the effect of the number of cars a household owns on VKT.

Unfortunately, we expect the ordinary least-squares (OLS) estimate of γ_1 to be biased. Unobservable individual parameters such as driving preferences may be correlated with both the number of household cars and VKT. An individual who likes to drive is more likely to buy an additional car than an individual who prefers taking the subway. Moreover, owning a car may increase an individual's job opportunities, raising income and allowing the individual to purchase an additional car.

To address these potential sources of bias, we restrict the sample to lottery participants and use the individual's lottery status to instrument for the number of cars. We use a two-stage least squares strategy, where the first stage is equation (1) with the number of household cars as the dependent variable. We use the predicted value $\widehat{Cars_i}$ in our second stage equation, control for entry month and other observables, and adjust standard errors to account for the first-stage prediction:

$$Y_i = \gamma_0 + \gamma_1 \widehat{Cars_i} + \gamma_2 X_i + \gamma_3 \eta_i + \epsilon_i \tag{3}$$

The dependent variables are similar to those used in the reduced-form estimation, and they include distance and time traveled as well as rush hour travel. This IV strategy is valid under two conditions: (a) conditional on date of entry, winning the lottery is independent of all individual characteristics that might affect ϵ_i; and (b) lottery status is a strong predictor of the number of cars. Both of these conditions were established previously: Table 2 supports assumption (a), and Table 3 supports assumption (b).

We interpret the IV estimate as the effect of adding a car for those who added one because they won the lottery. Obtaining an additional car has a number of mediating effects on VKT, such as the effect of the higher average fuel economy that results from obtaining a new car (since new cars typically have higher fuel economy than older cars).

The coefficient estimates are presented in Table 5.[13] Each coefficient estimate represents the effect of an additional car on the dependent variable for lottery losers. For example, according to row 1 of column 1, each additional car purchased by lottery losers would increase VKT by 12.2 km, almost tripling the average for losers of 6.7 km. Similarly, according to row 1 of column 2, each car added would raise time traveled using a car by 31.9 min, a large increase over the 18.6 min of average car time for lottery losers.

Because the commute to work can affect labor market outcomes, we focus on reported trips to work.[14] We also see very large changes in the distance commuted and average time spent commuting by car. Each car increases distance commuted by car by 5.8 km, which again would triple the average commute distance by car for losers of 2.8 km.

Results in the top panel show the effects of cars on travel behavior of lottery entrants. The bottom panel performs the same regressions, except that the dependent variable is the average for all household members of the lottery entrant. Because the unit of observation in these regressions is a lottery entrant, the definition of the dependent variables allows us to take advantage of

[13] The F-statistic for the first stage is 517.22, suggesting that this regression does not suffer from the problem of weak instruments bias.
[14] We define a trip as a "commute" if the destination is the office and the stated purpose of the trip is going to work.

Table 6
IV regressions on whether someone traveled during rush hour by car.

	Morning Rush Hour	Evening Rush Hour
Number of cars	0.332***	0.287***
	(0.032)	(0.034)
Age of member	−0.000	−0.001*
	(0.000)	(0.000)
Is female	−0.105***	−0.105***
	(0.010)	(0.006)
N	8057	8057
R^2	0.139	0.128

*$p < 0.10$, **$p < 0.05$, ***$p < 0.01$.
Regressions include only lottery entrants. All regressions include fixed effects for the day of the week of the interview, for the education level of the entrant, and for the month of entering the lottery. Standard errors are robust and clustered at the city district level.

the randomization of the lottery while characterizing the effects of cars on total household travel. We see the same pattern of results: each car causes large increases in the average distance and time traveled by car.

4.2. Effect on rush hour travel

We present our results on whether owning a car affects rush hour vehicle use in Table 6. Cars have a large effect on driving during rush hour: each additional car purchase induced by winning the lottery increases morning rush hour car use by 33.2 percentage points, and increases evening rush hour use by 28.7 percentage points.

5. Heterogeneity results

We examine whether the effects of the number of cars on travel behavior varies by the entrant's age or entry date. Tables documenting these results are relegated to the appendix for brevity.

First, we examine whether the effects of winning the lottery varies across age groups. We interact the lottery status with a dummy variable equal to one if the individual is older than 40 (that is, we continue to assume that age is exogenous to travel behavior).

Our results show no clear variation with age when we examine the effect of car ownership on either total travel or commute. Again, the main shifts appear to occur in the mode of transportation. Although the age interactions are not statistically significant for total distance and car distance (for both commuting trips and all trips), the age interactions are positive and at least marginally statistically significant for all bus and subway travel and for commuting travel by bus. These results suggest that obtaining a car may cause older individuals to reduce bus or subway travel less than do younger individuals, perhaps because of differential preferences for public transportation across age groups.

Second, we examine how entry date might affect travel behavior. Early lottery entrants may have the highest demand for cars; they also are more likely than later entrants to have had sufficient time to adjust their lives in response to a car, for example by changing jobs or housing. In these regressions, we interact entry year fixed effects with lottery status.

We first examine whether the number of cars is affected by lottery entry date. We find that entrants in 2012 have the most cars and 2014 entrants have the least cars. However, 2011 entrants and 2013 entrants have very similar numbers of cars.

We find no statistically significant differences of travel behavior by entry date. Although there is some difference in the point estimates between entry years, there is no pattern. Our point estimates suggest that 2013 entrants increased their total travel more than did 2011 entrants, but 2014 entrants decreased travel. For commuting distance, 2012 entrants increased travel distance more than 2011 entrants, and 2013 entrants decreased travel. Differences across entry years are not statistically significant, and we conclude that date of entry seems to have no effect on our primary results.

6. Calculations of policy impacts

6.1. The potential aggregate impact of vehicle ownership restrictions on the vehicle stock

We use the reduced-form estimates to calculate the effect of ownership restrictions on the stock of cars in Beijing. As we noted in the introduction, these are partial equilibrium calculations, in the sense that we hold fixed at observed levels congestion and other factors that may affect vehicle ownership.

More specifically, we assume that if the lottery had not existed, individuals in households who entered the lottery and lost would have been as likely to purchase a car as individuals who entered the lottery at the same time and won. This assumption is supported by the observation that winners and losers are quite similar along observable dimensions (see Table 2), and that randomization of the lottery implies that lottery losers would behave like winners if they had the right to obtain a car. We also assume that individuals who do not enter the lottery would not have purchased a car in the absence of the lottery policy. The lottery entry process involves a short online application with no entry fee; as a result, the cost of entering the lottery is near zero and anyone wishing to purchase a car should have entered.

Under the first assumption, our estimates from Table 3 suggest that lottery losers have about 0.64 fewer cars than lottery winners, a reduction of more than half from the 1.21 cars of lottery winners. The estimate of 0.64 is the average difference of the number of cars between winners and losers.[15]

If all losers were hypothetically given the right to obtain an additional car, some of the losers may decide not to obtain a car. The reason is that, to increase their chances of winning, some households have multiple entrants even if they intend to obtain only one additional car. For example, consider a household that has one winner and one loser, but which only wants one additional car. If the loser were given the right to obtain a car, the loser would choose not to obtain a car because the winner already obtained one.

As a conservative assumption, we assume that for any household with multiple entrants that include at least one winner, the household would not obtain multiple cars if more than one loser were given the right to obtain a new car. Of the 7278 losers in the survey data, there are 6275 losers from households that do not contain any winners. This assumption is conservative to the extent that any households in our data wish to add multiple vehicles. Under this assumption, we multiply 0.64 cars by the number of households without any winners to determine that Beijing vehicle ownership restrictions removed $(0.64*6275) = 4016$ new cars from entrants in our sample.

Above we noted the possibility that the lottery pulls forward a certain amount of sales, which arises from the fact that the lottery creates uncertainty about when a household can obtain a new car. Because of this uncertainty, individuals may enter the lottery prior to the date they would have purchased a car in the absence of the lottery. If we do not adjust our estimates by this effect, we would overstate the effect of the lottery on the stock of cars. However, as we explain next we can obtain an upper bound on this effect, which yields a lower bound on the change in car stock.

Our data show that 1.10 million people entered the lottery in 2011, with this level continuing into early 2012. During the 12-month period prior to the announcement of the lottery, total new car sales in Beijing were 832,416. If we assume that in the absence of the lottery, vehicle sales would have remained at pre-lottery levels, we estimate that (100%∗(1.10 million - 832,416)/1.10 million) = 24% of lottery participants were pulled forward. This estimate of the pull-forward effect is an upper bound because it does not account for the fact that about 10% of lottery winners do not purchase a car. Moreover, the use of 2010 sales to proxy for counterfactual 2011 sales is also likely to over-estimate this effect, because vehicle sales in Beijing would probably have increased in the absence of the lottery. Yang et al. (2014) show that car sales increased at double digit growth rates in the years prior to the lottery.

Adjusting our estimate of 4016 cars removed by the pull-forward effect yields an estimate of $(4016*(1–0.24)) = 3031$ cars removed by the lottery. The full BTRC survey, representative of the entire city of Beijing and including nonparticipants, has 19,217 cars among those surveyed. This implies that the stock of cars in Beijing would have been (100∗3031/19,217) = 16% bigger in the absence of ownership restrictions.

We calculate that the stock of vehicles in Beijing has been reduced by (100%∗3031/(3031 + 19,217)) = 14% in 2014, a larger decrease than previous work has suggested. Yang et al. (2014) predicted that vehicle ownership restrictions would reduce the stock of cars in Beijing by 11% in the year 2020. While that work used simple extrapolation techniques to estimate the counterfactual, this present paper has the advantage of natural experiment-based identification. Moreover, Yang et al. overestimated the stock of cars under the policy because they assumed that each lottery winner would add one car to the stock of cars of Beijing; this does not account for the fact that many lottery winners choose not to add a car.

6.2. The potential aggregate impact of vehicle ownership restrictions on travel

The above estimates yield the average changes in car use for lottery losers if they were allowed to purchase cars. In this subsection, we place these individual-level results into the broader policy context of Beijing by examining three city-level outcomes: total daily VKT, morning rush hour car use, and evening rush hour car use. These calculations are not meant to estimate the counterfactual vehicle usage levels if vehicle ownership restrictions were not in place, but instead are intended to show how sizeable the reductions of car usage are compared to existing usage.

These calculations depend on three assumptions: first, that losers would behave like winners in the absence of the lottery; second, that lottery winners in the absence of vehicle ownership restrictions would behave in the same way; and third, that the behavior of non-entrants would not change in the absence of the lottery. In other words, we are able to examine the direct effects of vehicle ownership restrictions, but not the indirect effects. In particular, if vehicle ownership restrictions reduced congestion, we are unable to observe travel behavior in the presence of the counterfactual congestion. As with the vehicle stock calculations, because of this assumption we consider the results to be partial equilibrium.

We first examine the importance of vehicle ownership restrictions on Beijing's total daily VKT. According to reduced-form estimates from Table 3, giving a loser the right to obtain a car would increase VKT by 7.9 km. Since there are 6275 lottery

[15] We note that lottery entrants include people who entered between 2011 and 2014. Our estimate is therefore an average treatment effect over these years.

losers, total VKT for our sample would be increased by $(7.9*6275 =)$ 49,573 km.[16] This represents a 72% increase in VKT among losers, a 49% increase among all lottery participants, and a $(100\%*49{,}573/336{,}298 =)$ 15% increase among all households in our sample.[17]

We next study the importance of vehicle ownership restrictions on morning and evening rush hour car use. Based on the reduced-form estimates from Table 3, giving losers the right to purchase cars would cause them to drive an additional $(0.211*6275 =)$ 1324 cars during the morning rush hour and $(0.183*6275 =)$ 1148 cars during the evening rush hour. The full survey sample includes 13,555 individuals who travel by car during the morning rush hour period and 12,152 individuals who travel by car during the evening rush hour period. If all losers were given the right to buy cars, morning and evening rush hour car use would increase by 10%, meaning that the lottery has reduced rush hour car use by 9%. These are large effects that suggest that the policy has heavily reduced congestion during peak hours.

7. Discussion and conclusion

The Beijing license plate lottery has sharply reduced vehicle ownership, total travel, and driving during morning and evening rush hours. Winners of the lottery own more than twice as many cars as losers. Moreover, winners drive twice as much as losers, both overall and during morning and evening rush hours. These findings contrast with the mixed evidence regarding the success of vehicle driving restrictions, and they suggest that restricting vehicle ownership can sharply reduce traffic congestion, accidents, and pollution.

We also report partial equilibrium estimates of the effects of the lottery on the total stock of cars in Beijing and on total travel. Restricting vehicle ownership has reduced the total stock of cars by 14%, a large amount. The results imply that removing the lottery would increase total VKT in Beijing by 15% and increase morning and evening rush hour car use by 10%. The lottery has sharply reduced driving, which should result in large decreases in congestion. Reductions in driving and congestion would also mean lower air pollution and greenhouse gas emissions. These findings point to the effectiveness of vehicle ownership restriction policies at reducing driving. However, these calculations may overstate the aggregate effects of the lottery to the extent that the initial drop in congestion caused by the lottery increases vehicle ownership and driving in the long run.

We find that each additional car roughly triples VKT, which has implications for long-run growth in privately owned vehicle use and fuel consumption. If the relationship holds more broadly, it suggests that future fuel consumption, pollution emissions, and vehicle usage may increase even more quickly than vehicle ownership. Projecting fuel consumption and pollution emissions depends partly on projecting vehicle ownership, a finding that may be useful in the important literature on vehicular contributions to environmental problems.

We offer a few caveats related to the external validity of our findings, besides those already noted. First, we believe that our findings apply primarily to large urban cities like Beijing, which combines notoriously high congestion with an extensive public transportation system. To avoid decreasing travel distances or times, other cities contemplating vehicle ownership restrictions should have public transportation in place to provide substitutes for cars taken off the road.

Second, car ownership restrictions may reduce congestion (Yang et al., 2014) and increase the value and use of new cars. The effects on car use of newly-enacted ownership restrictions, such as the Beijing license plate lottery, may differ from the effects of long-standing policies.

Third, the mechanism of the lottery required only an online application and entry was free. As a result, some Beijing residents entered the lottery because they anticipated the possibility of needing a car, and purchased a car when they won because they did not expect to be able to win a second time. Many lottery winners also did not add vehicles to their households. Therefore, the lottery should be regarded as a random mechanism allocating *options* to purchase cars, rather than allocating cars directly.

Finally, as we noted above, taxi use and ridesharing was relatively uncommon during our sample period. The fact that taxi use remained low throughout the sample suggests that restricting ownership did not appreciably affect taxi use. However, it is possible that continued ownership restrictions could cause nontrival increases in ridesharing, which is an important topic for future research.

[16] Above we noted the possibility that the lottery could create a pull-forward effect, in which households that would have otherwise delayed purchasing a vehicle instead enter the lottery. Such an effect would not bias the reduced-form estimates. To the extent that such households drive less during the travel day than other households, we would underestimate the effect of the lottery on aggregate VKT.

[17] To put this figure in context, about 20% of households had at least one member enter the lottery. Households of lottery entrants account for about 32% of all driving.

Appendix A

Appendix Table 1
Comparability of Lottery Entrants Winning and Not Winning the Lottery, by Year of Entry.

	Winners	Losers	Difference
	2011		
Female	0.381	0.377	0.004
Birth year	1975.645	1974.500	1.144*
High school graduation rate	0.876	0.862	0.014
College graduation rate	0.668	0.620	0.047*
Is working full-time	0.841	0.800	0.041*
N	346	1805	
	2012		
Female	0.383	0.393	−0.010
Birth year	1976.642	1975.502	1.141
High school graduation rate	0.825	0.851	−0.027
College graduation rate	0.606	0.611	−0.006
Is working full-time	0.836	0.827	0.008
N	274	2301	
	2013		
Female	0.432	0.430	0.002
Birth year	1974.985	1976.624	−1.639
High school graduation rate	0.841	0.857	−0.016
College graduation rate	0.591	0.619	−0.028
Is working full-time	0.773	0.814	−0.041
N	132	2002	
	2014		
Female	0.333	0.457	−0.124
Birth year	1973.926	1976.929	−3.003
High school graduation rate	0.741	0.880	−0.139**
College graduation rate	0.519	0.662	−0.143
Is working full-time	0.815	0.781	0.033
N	27	1171	

$^{*}p < 0.10, ^{**}p < 0.05, ^{***}p < 0.01.$

Appendix Table 2
IV Regressions on Total Travel Distance with Age Interactions for Lottery Entrants.

	All Distance	By Car	By Bus	By Subway	By Bike/Foot
	All Travel				
Number of cars	0.313	16.859***	−10.039***	−6.134***	−1.534
	(6.993)	(5.571)	(3.228)	(2.007)	(1.224)
(Number of cars)*(Age)	0.085	−0.122	0.136**	0.090**	0.019
	(0.165)	(0.137)	(0.067)	(0.036)	(0.045)
Age of member	−0.389***	−0.029	−0.238***	−0.159***	0.019
	(0.090)	(0.069)	(0.056)	(0.033)	(0.030)
Is Female	−5.873***	−5.510***	−0.292	−0.014	0.164
	(0.954)	(0.677)	(0.599)	(0.275)	(0.272)
N	7015	7015	7015	7015	7015
R^2	0.028	0.096	0.035	0.062	0.048
	Commute				
Number of cars	−0.125	7.888*	−6.514***	−1.846	0.030
	(5.206)	(4.230)	(1.978)	(2.031)	(0.566)
(Number of cars)*(Age)	0.038	−0.058	0.119***	0.017	−0.031*
	(0.132)	(0.111)	(0.043)	(0.041)	(0.018)
Age of member	−0.221***	−0.010	−0.147***	−0.104***	0.042***
	(0.080)	(0.062)	(0.031)	(0.033)	(0.016)
Is Female	−2.503***	−2.445***	−0.327	0.219	0.100
	(0.615)	(0.443)	(0.431)	(0.245)	(0.089)
N	5556	5556	5556	5556	5556
R^2	0.030	0.104	0.025	0.056	0.060

$^{*}p < 0.10, ^{**}p < 0.05, ^{***}p < 0.01.$
Regressions include only lottery entrants. All regressions include fixed effects for the day of the week of the interview, for the education level of the entrant, and for the month of entering the lottery. Standard errors are robust and clustered at the city district level.

Appendix Table 3
First-stage Regressions with Year of Entry Interactions for Lottery Entrants.

	Number of Cars
Won Lottery	0.617***
	(0.037)
(Won Lottery)∗(2012 Entry)	0.083*
	(0.047)
(Won Lottery)∗(2013 Entry)	0.028
	(0.062)
(Won Lottery)∗(2014 Entry)	−0.174
	(0.146)
N	7015

*$p < 0.10$, **$p < 0.05$, ***$p < 0.01$.
Regressions include only lottery entrants. All regressions include fixed effects for the day of the week of the interview, for the education level of the entrant, and for the month of entering the lottery. Standard errors are robust and clustered at the city district level.

Appendix Table 4
Reduced Form Regressions with Interactions for Age Dummy.

	All Distance	By Car	By Bus	By Subway	By Bike/Foot
	All Travel				
Won the lottery	1.367	8.626***	−4.250***	−2.289***	−0.759*
	(1.917)	(1.467)	(1.001)	(0.659)	(0.371)
(Won Lottery)∗(Age > 40)	2.250	−1.830	2.725*	1.348**	0.556
	(3.179)	(2.223)	(1.420)	(0.604)	(1.177)
Age of member	−0.349***	−0.101***	−0.165***	−0.109***	0.029*
	(0.047)	(0.027)	(0.034)	(0.016)	(0.016)
Is Female	−5.211***	−3.383***	−1.106	−0.461**	0.025
	(0.893)	(0.612)	(0.649)	(0.213)	(0.190)
N	7015	7015	7015	7015	7015
R^2	0.035	0.032	0.023	0.055	0.044
	Commute				
Won the lottery	0.174	3.376***	−1.828***	−0.838	−0.559***
	(1.075)	(0.810)	(0.493)	(0.488)	(0.090)
(Won Lottery)∗(Age > 40)	0.753	−1.164	1.586**	0.490	−0.080
	(1.436)	(1.150)	(0.671)	(0.395)	(0.143)
Age of member	−0.223***	−0.052***	−0.088***	−0.077***	−0.002
	(0.025)	(0.013)	(0.013)	(0.010)	(0.005)
Is Female	−2.498***	−1.358***	−0.788*	−0.076	−0.226***
	(0.548)	(0.305)	(0.379)	(0.142)	(0.064)
N	7015	7015	7015	7015	7015
R^2	0.062	0.033	0.024	0.049	0.030

*$p < 0.10$, **$p < 0.05$, ***$p < 0.01$.
Regressions include only lottery entrants. All regressions include fixed effects for the day of the week of the interview, for the education level of the entrant, and for the month of entering the lottery. Standard errors are robust and clustered at the city district level.

Appendix Table 5
Reduced Form Regressions with Interactions for Lottery Year of Entry Dummies.

	All Distance	By Car	By Bus	By Subway	By Bike/Foot
	All Travel				
(Won Lottery)*(2011 Entry)	1.010	8.070***	−4.199***	−2.828***	−0.873*
	(2.060)	(1.841)	(1.432)	(0.561)	(0.498)
(Won Lottery)*(2012 Entry)	2.739	8.585***	−2.980***	−2.216**	−1.330
	(2.144)	(2.388)	(1.004)	(0.897)	(0.812)
(Won Lottery)*(2013 Entry)	5.194*	10.718***	−7.260***	−1.097	0.904
	(2.476)	(2.118)	(1.116)	(1.366)	(2.190)
(Won Lottery)*(2014 Entry)	−0.967	5.521	−3.312	−2.287	−1.602
	(3.824)	(3.236)	(3.094)	(1.946)	(0.974)
Age of member	−0.341***	−0.102***	−0.165***	−0.109***	0.029*
	(0.051)	(0.027)	(0.034)	(0.016)	(0.016)
Is Female	−5.215***	−3.385***	−1.102	−0.461**	0.023
	(0.899)	(0.610)	(0.646)	(0.213)	(0.188)
N	7015	7015	7015	7015	7015
R^2	0.035	0.032	0.023	0.055	0.044
	Commute				
(Won Lottery)*(2011 Entry)	0.272	3.440***	−1.618**	−1.360***	−0.459***
	(0.981)	(0.974)	(0.656)	(0.339)	(0.136)
(Won Lottery)*(2012 Entry)	0.975	3.429***	−1.379**	−0.543	−0.780***
	(0.928)	(0.972)	(0.614)	(0.757)	(0.161)
(Won Lottery)*(2013 Entry)	−0.287	3.050***	−3.299***	−0.310	−0.409*
	(1.326)	(1.000)	(0.574)	(0.820)	(0.196)
(Won Lottery)*(2014 Entry)	1.816	3.656*	−1.860	−0.099	−0.213
	(1.794)	(1.756)	(1.230)	(2.053)	(0.484)
Age of member	−0.220***	−0.052***	−0.087***	−0.076***	−0.002
	(0.025)	(0.013)	(0.013)	(0.010)	(0.005)
Is Female	−2.497***	−1.358***	−0.786*	−0.076	−0.226***
	(0.549)	(0.304)	(0.378)	(0.143)	(0.064)
N	7015	7015	7015	7015	7015
R^2	0.063	0.033	0.024	0.049	0.030

$^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$.
Regressions include only lottery entrants. All regressions include fixed effects for the day of the week of the interview, for the education level of the entrant, and for the month of entering the lottery. Standard errors are robust and clustered at the city district level.

Appendix Table 6
IV Regressions on Total Travel Distance with Year of Entry Interactions for Lottery Entrants.

	All Distance	By Car	By Bus	By Subway	By Bike/Foot
	All Travel				
Number of cars	1.646	11.871***	−4.976***	−3.704***	−1.064**
	(3.156)	(2.543)	(1.752)	(0.710)	(0.496)
(Number cars)∗(2012 Entry)	2.262	−0.678	2.336	1.303	−0.532
	(3.493)	(3.363)	(2.215)	(1.130)	(0.979)
(Number cars)∗(2013 Entry)	6.458	3.543	−4.454**	2.915	2.855
	(4.797)	(4.389)	(2.258)	(2.134)	(3.965)
(Number cars)∗(2014 Entry)	−4.076	−1.528	0.618	−0.042	−2.061
	(8.981)	(7.487)	(5.960)	(4.317)	(2.324)
Age of member	−0.340***	−0.102***	−0.156***	−0.106***	0.029**
	(0.050)	(0.029)	(0.032)	(0.015)	(0.015)
Is Female	−5.958***	−5.654***	−0.071	−0.054	0.096
	(0.965)	(0.689)	(0.559)	(0.325)	(0.341)
N	7019	7019	7019	7019	7019
R^2	0.025	0.092	0.025	0.058	0.039
	Commute				
Number of cars	0.546	5.881***	−1.857**	−2.310***	−1.037***
	(1.737)	(1.310)	(0.938)	(0.464)	(0.314)
(Number cars)∗(2012 Entry)	1.891	−0.044	0.608	1.667	−0.319
	(1.739)	(1.605)	(1.553)	(1.120)	(0.406)
(Number cars)∗(2013 Entry)	0.351	−0.378	−2.811**	2.359	0.370
	(2.501)	(1.852)	(1.308)	(1.601)	(0.350)
(Number cars)∗(2014 Entry)	−1.437	−0.694	−2.289	1.814	−0.188
	(3.525)	(3.207)	(2.450)	(3.887)	(0.898)
Age of member	−0.197***	−0.044***	−0.075***	−0.095***	0.023***
	(0.030)	(0.016)	(0.016)	(0.015)	(0.008)
Is Female	−2.453***	−2.432***	−0.160	0.142	0.077
	(0.623)	(0.462)	(0.403)	(0.274)	(0.099)
N	5556	5556	5556	5556	5556
R^2	0.028	0.103	0.014	0.049	0.061

$^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$.
Regressions include only lottery entrants. All regressions include fixed effects for the day of the week of the interview, for the education level of the entrant, and for the month of entering the lottery. Standard errors are robust and clustered at the city district level.

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jeem.2019.102269.

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