How Does a Driving Restriction Affect Transportation Patterns?

The Medium-Run Evidence from Beijing

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Abstract

This paper uses data from 2009 to 2014 to study the short- to medium-run effect of a driving restriction on transportation patterns in Beijing. The driving restriction specifies two numbers for each weekday so that cars with license plates ending in either of the numbers are banned from driving on that date. Because very few Chinese want to have their car licenses ending in 4, many more cars are driving on days when 4 is banned. Exploiting this variation, the analysis shows that the driving restriction significantly improves traffic conditions in the restricted period without worsening it in the unrestricted period. When cars are banned, bus and taxi ridership increases significantly, but very few drivers were motivated to take rail. With the implementation of the driving restriction policy, the improvement effect on the evening traffic conditions becomes stronger over the study period, which can be largely attributed to the car purchase quota and the more stringent punishment for violating the driving restriction, both of which started in 2011.

Key Words: driving restriction, traffic congestion, transportation choice

JEL Codes: Q58, R41, R42, D01

Contents

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1. Introduction

Over the past twenty years, Beijing has experienced unprecedented growth in the number of motor vehicles. From 2001 to 2014, the total number of motor vehicles grew from 1.1 million to 5.4 million, with the number of private cars growing from about 0.51 million to 4.3 million. During the same period, Beijing invested heavily in the construction of roads and other public transportation infrastructure; from 2000 to 2009, roads increased from 2470 kilometers to 6247 kilometers in the urban areas.[1] However, like many other big cities, Beijing's efforts in road construction were dwarfed by the increase of new vehicles, and traffic congestion became worse. Beijing has been ranked as one of the most congested cities in the world by many international organizations (for example, IBM 2010). Besides causing serious traffic congestion, the growing fleet of cars also emits a massive amount of pollutants, which are a major source of Beijing's poor air quality.

A driving restriction policy has become an increasingly popular response to these problems. The restriction could be every other day or once a week, according to the ending number of a car's license plate. During the 2008 Olympics, in order to improve traffic conditions and air quality, Beijing experimented with many temporary measures, one of which was a driving restriction policy that prohibited drivers from driving every other day (the odd-even driving restriction). After the Olympics, the city government decided to continue the driving restriction but modified the rule so that cars were prevented from driving once every week (the once-a-week driving restriction). Mexico City, Bogotá, Santiago, São Paulo, and New Delhi have all experimented with driving restriction policies in one way or another.

A number of studies have explored the effects of driving restriction policies on traffic and air quality (Cao et al. 2014; David 2008; Gallego et al. 2013; Sun et al. 2014; Viard and Fu

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[1] Source: Beijing Transportation Research Center.

2015). Most studies rely on the comparison between dates immediately before and after the launch of the restriction policy. In addition, although various studies differ in their conclusions on whether the driving restriction policy achieved its intended benefits, they seldom look at the issue from the perspective of cost – the imposed substitution between cars and other methods or even the elimination of trips. This study intends to analyze how the restriction policy affects transportation arrangements over a long period, using data for more than five years. It leverages the daily variation in the share of cars that are banned from driving due to the cultural avoidance of the number 4. Exploiting bus and subway passenger ridership and taxi flow information as well as the traffic performance index, we are able to shed light on how driving restrictions affect transportation patterns in Beijing.

The number 4 is considered unlucky in Chinese folk customs and very few cars have a license plate ending in 4. [2] On days when the number 4 is banned (hereafter, the Number-4 days), only 14% of cars are restricted from driving, while on other weekdays 21% of cars are restricted. This generates a considerable variation in the number of cars on the road on different days of the week. In addition, the arrangement of plate numbers on days of the week is predetermined and rescheduled periodically. Employing such exogeneity, this paper analyzes the effects of this driving restriction on traffic congestion and passenger trips by bus, rail and taxi in Beijing.

The empirical analysis indicates that on the Number-4 days, when fewer cars are restricted from driving, traffic is more congested. Given that on average 20% of cars are banned each day, the driving restriction saves 34% of the standard travelling time (the required travelling time when there is no traffic jam) in the morning peak hours and 57% in the evening peak hours. The impact covers the whole restriction period and expands to two hours after the official ending time of the restriction. These results suggest that the driving restriction is effective in affecting driving behavior, and that the policy improves traffic conditions during the regulated period without worsening it in the non-regulated period. The effect of the driving restriction remains constant for the morning traffic index, but exhibits an increasing trend over the study period for the evening traffic index. The increasing restriction effect during the evening rush hours can be largely explained by the launch of a car purchase quota and more stringent punishment for violating the driving restriction.

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[2] The drivers are provided a list of randomly generated license plate numbers from which to choose. We observed that people have a preference to avoid the number 4.

The driving restriction motivates more use of public transit; roughly four cars banned from driving can motivate one more bus passenger trip. However, the substitution toward rail passenger trips is small and statistically insignificant, although many new rail lines were opened during the period. The driving restriction also increases the use of taxis. The hours with more taxi ridership start and end at the same time as the restriction policy, but the effect is not significant throughout the whole restricted period.

This study contributes to the literature in two ways. First, it explores how people cope with the unavailability of car driving and estimates the effect of the driving restriction policy on transportation patterns. Second, while existing evidence focuses on the initial impact of the driving restriction, this study, which exploits daily data for more than five years, also sheds light on how the impacts evolve over time and in relationship to other policies or events.

This paper is organized as follows. Section 2 provides background information on Beijing traffic and a literature review on driving restriction policies. Section 3 introduces the data we used. Section 4 describes the empirical strategy. Section 5 presents the empirical results on the traffic index, bus and subway ridership, and the use of taxis. Section 6 concludes.

2. Background and Literature Review

2.1 Background

To ensure good air quality and smooth traffic during the 2008 Beijing Summer Olympics, the government banned vehicles from being used every other day, depending on whether the last digit of one's license plate was odd or even (the odd-even driving restriction). Shortly after the Olympics, starting on October 11, 2008, Beijing implemented a once-a-week restriction policy that bans vehicles from driving on one weekday every week (the once-a-week driving restriction). Restrictions do not apply on the weekend. The restriction schedule alternates periodically (once a month before April 5, 2009 and every 13 weeks thereafter). For example, during the first month of the policy, cars with license plate numbers ending with digits 1 and 6 were restricted on Monday, 2 and 7 on Tuesday, 3 and 8 on Wednesday, and so on. One month after that, the restricted numbers on Monday were changed to 5 and 0. Therefore, numbers are not restricted on the same weekdays over time. Table 1 presents the restriction schedule.

The restricted area is within the 5th Ring Road (the central urbanized area of Beijing). Initially, the once-a-week rule was enforced from 6 a.m. to 9 p.m. Starting on April 10, 2009, the daily restriction period was changed to between 7 a.m. and 8 p.m. The regulation applies to all

vehicles of both firms and households, with exceptions for buses, taxis, and vehicles of the police department and the army.

Before January 2011, the punishment for violating the restriction was a penalty of 100 yuan, which could be imposed only once a day; then it was changed to 100 yuan, which could be imposed every three hours. Thus, the punishment became more stringent for people who use cars frequently. For nonlocal cars, besides fines, the drivers are also punished with license points.

To further improve traffic conditions and air quality, starting in 2011, the Beijing government set the total number of car licenses that can be issued each year at the city level. Potential car buyers have to win a quota for a car plate through a lottery system before obtaining a car license. The car plate quota limits the increase of car ownership. Figure 1 shows that the growth rate of car ownership dropped dramatically, from 23.6% in 2010 to 3.5% in 2011.

2.2 Literature Review

Similar driving restriction policies have been implemented in a number of cities, such as Mexico City, Bogotá in Columbia, Santiago in Chile, and São Paulo in Brazil. In 1989, Mexico started a once-a-week driving restriction. Eskeland and Feyzioglu (1997) compare before and after the implementation, and show that the restriction increased gasoline demand, except in the first quarter after implementation, and caused more purchase of used cars. Their paper also hints at no impact on air quality. Davis (2008) uses the regression discontinuity method (RD) to show that the driving restriction has no impact on air quality. Further analysis shows that the driving restriction did not decrease gasoline consumption, but instead was associated with an increase in the total number of private vehicles in circulation, as well as an increasing proportion of high-emissions vehicles.

Since the launch of the driving restriction policy in Beijing in 2008, there have been several studies exploring its impact from various aspects. Using the same RD method as used by Davis (2008), Cao et al. (2014) provides similar results in Beijing: negligible impact on air quality and some evidence of additional car purchases. However, using a similar RD method but slightly different data, Viard and Fu (2015) demonstrate results that are sharply different from those in Cao et al. (2014). They find that the restriction has significantly improved air quality – the air pollution index decreased by 8% after the implementation of the driving restriction. In addition, workers with discretionary jobs increased television viewing time by 1.7 to 2.3% after the implementation of the restriction, which suggests that they are working less.

Besides the RD method, a few scholars have explored the exogenous variation in the number of cars banned on the road due to the number 4. In the Chinese culture, "4" is a less

prosperous number, and many people try to avoid 4 on their license plate. Therefore, when the banned numbers are 4 and 9, fewer cars are banned. Sun et al. (2014) use data from January 2009 to April 2011, and show that traffic conditions are much worse when cars with the license plate number 4 are the ones restricted from driving, suggesting the effectiveness of the restriction on traffic congestion. However, the concentration of PM10 does not vary accordingly. Instead, Sun et al. further present an inverted U-shaped relationship between traffic conditions and air quality, with the turning point in the middle of the traffic index. Using 2012 data, Zhong (2014) presents findings that are quite different from those of Sun et al. In Zhong's analysis, the driving restriction policy improves air quality; on days when the number 4 is banned, the concentration of nitrogen dioxide (NO2) goes up. Besides, Zhong also shows increased ambulance calls as the consequence of worse air quality. Anderson et al. (2015) also exploit the variation in the number of restricted cars due to the number 4, and find that Beijing residents reported a higher level of happiness when there is less traffic congestion.

Exploring how people respond to driving restrictions is important for overall welfare analysis of the driving restriction policy. Davis (2008) suggests that the restriction does not promote the use of public transit in Mexico City. De Grange and Troncoso (2011) find that the short-run driving restriction on air pollution pre-emergency days increased the flow of passengers to the Metro by about 3%, while bus usage showed no statistically significant increase. Gu et al. (2014) explore individual-level data in 2010 and show that the driving restriction reduced car trips in the restricted period, and increased the use of bus, bicycles and electric bicycles in Beijing. Unlike Gu et al., our study focuses on the aggregate impact on transportation patterns, and we are especially interested in how the restriction impact evolves over more than five years.

3. Data

Six sets of data are used in the analysis: percentage of cars ending with each number, the arrangement of banned numbers, traffic performance index, counts of bus passenger trips and rail ridership, records of taxi trips, and data on weather.

Table 2 shows the percentage of cars ending with various numbers. The distribution is largely constant over the years, but the percentages differ remarkably across the numbers. While other ending numbers are associated with around 10% of cars, which is a "fair" share, the number 4 accounts for only 1-3% of the cars. The strong avoidance of the number 4 has the result that only 14% of cars are banned on days when the numbers 4 and 9 are restricted, while 20-22% of cars are restricted on other days, as shown in the lower panel of Table 2.

Two variables can capture the sizable variation in the number of cars allowed on the road. One is whether the number 4 is banned on a certain date; this variable is *tailno4*, which equals one if the number 4 is banned and zero otherwise. The other is the percentage of cars being allowed on the road, *tailpct*, which equals 100 minus the percentage of cars that are restricted. The variable *tailno4* has an intuitive interpretation, but the variable *tailpct* also captures the variations in the percentage of cars across other numbers.

The traffic performance index (TPI) ranges from 0 to 10, with a larger value indicating worse traffic congestion. Table 3 helps illustrate the correlation between TPI and the needed travel time. If the travel time is 30 minutes when traffic conditions are "smooth," it would take about an hour if the index gets to 6-8 (moderately congested). The TPI data are collected by the Beijing Municipal Commission of Transport. We have two versions of the TPI data: daily data during the AM rush hour (7-9 a.m.) and the PM rush hour (5-7 p.m.) from Jan. 1, 2009 to May 30, 2014, and hourly data for all of 2013. Both versions cover the within-5th ring area. [3]

Data on bus and rail passenger trips are reported by the public transportation companies. They are daily counts for the whole city. An example may help to explain the data. Say a person takes Bus A, then transfers to Bus B, then to Rail X and to Rail Y, and eventually gets on Bus C to her destination. This travel contributes three units of bus ridership and two of rail ridership. The data period is from Jan. 1, 2009 to May 30, 2014.

The upper panel of Figure 3 illustrates the traffic indices during the AM rush hours (7-9 a.m.) and the PM rush hour (5-7 p.m.), and the lower panel shows the bus and rail ridership. In all graphs, dates are separated into two types: regular weekdays and "irregular dates" that include weekends, holidays, and dates around the Chinese New Year (defined as starting from one week before the lunar New Year and ending fifteen days after the lunar New Year). The pattern on irregular dates is quite different from that on regular weekdays. On weekends, there is very little traffic during the 7-9 a.m. period, and the bus and rail counts are very low too. As Beijing is a big immigrant city, many people leave Beijing to visit their hometown or go for vacation around the lunar New Year, which expands beyond the official holidays. The data around the lunar New Year form the fringe-like shape in the graphs; they are very different from those on the regular

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[3] Our daily data are different from the publicly available data published online by the Beijing Municipal Commission of Transport. The commission has modified the calculation formula to improve the index. The public data are the same indices as were published then, and do not reflect such improvement. Instead, our indices are calculated by feeding the raw data to the improved formula, so they are free of possible manipulation at the thresholds. For 2011, the index for the within-5th-ring area is the simple average of that for the within-4th-ring area and the between-4th-and-5th-ring area.

dates. Given that the variations in traffic during the irregular dates are largely uncorrelated with the driving restriction policy, we exclude the irregular dates in the main analysis.

Taxi data are collected from a taxi company, which randomly samples 20 cabs. Ten cabs have a two-driver shift over the 24-hour period, and the other ten cabs are driven by only one driver. Based on the transaction records, we calculate the paid ridership and paid miles at the car level on each date. In addition, we also aggregate the 20 cabs and generate taxi ridership for each hour.[4] The period covers June 1, 2011 to May 30, 2014.

The weather variables are taken from the China Meteorological Data Sharing Service System, including daily average rain, temperature, humidity, barometric pressure, sunshine and maximum wind speed. Table 4 shows the summary statistics of various variables. We exclude irregular dates from this table and all the analyses below.

The data period also saw several important events related to traffic: the car purchase quota, the more stringent punishment for violating the driving restriction, the start of several new subway lines, and the increase in taxi fees. Table 5 lists the time of the events. We generate a dummy variable for each event time. To note, the car purchase quota, the increasing punishment and the five new rail lines were started within several days of each other, so only one dummy variable is generated to represent all these events.

4. Empirical Strategy

Several special features of the once-a-week driving restriction policy in Beijing offer an opportunity for exploring the impact of the driving restriction. On one hand, as shown in Table 2, the traditional avoidance of the number 4 generates sizable variations in the number of cars that are banned across the days of the week. On the other hand, the schedule of banned numbers is pre-determined and rotates periodically. The number 4 is banned every five days (holidays may slightly break the pattern). Therefore, the dates on which 4 is banned are not likely to be different from other dates except that more cars are allowed to drive. Equation 1 tests the exogeneity of the restriction variables using the weather data. The key predictor $tailpct_t$ is the percentage of cars that are allowed to drive. We can substitute $tailpct_t$ with $tailno4_t$ to indicate whether the number 4 is restricted. The set of dummy variables $weekday_{2-5}$ indicates Tuesday to Friday, with Monday as the omitted control. Table 6 confirms the null effect.

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[4] We count passenger trips according to the starting time.

$$Weather_t = \beta_0 + \beta_1 tailpct_t + \beta_{2-5}\, weekday_{2-5,\,t} + e_t \tag{1}$$

As the restriction variables are not correlated with any factors that could possibly affect transportation choices after controlling for the days of week, it is straightforward to estimate the effect of the driving restriction on various outcomes, using a similar equation as simple as Equation 1. However, to reduce standard errors and to adjust for possible minor bias, we can add additional control variables, as in Equation 2. The outcomes can be TPI, bus, rail or taxi ridership. The variable t is calculated by the number of days starting from 1/1/2009 divided by 365.[5] The variables $month_{2-12,t}$ are the eleven monthly dummies, with January as the omitted control. Figure 2 shows a roughly linear time trend for the rail ridership and also some seasonal patterns in all the graphs. These patterns, together with other possible time trend or seasonal patterns, justify the control of t and $month_{2-12,t}$. The set of the event dummies $line_{1-5,t}$ represents whether or not rail lines are available, and $taxi$ indicates whether or not the taxi fees were increased.[6] The weather variables include rain, temperature, humidity, barometric pressure, sunshine and maximum wind speed. The regression is a time series regression; but, as both variables $tailpct$ and $tailno4$ are stationary, we can directly run an OLS to obtain meaningful results. We use robust s.e. to account for possible heterogeneity in the error term.

$$\begin{aligned} Outcome_t = \beta_0 + \beta_1 tailpct_t + \beta_{2-5}\, weekday_{2-5,\,t} + \theta_1 t + \theta_{2-12} month_{2-12,t} \\ + \gamma_{1-5} line_{1-5,t} + \gamma_6 taxi_t + \delta weather_t + e \end{aligned} \tag{2}$$

To explore how the effects of the driving restriction evolve over time, we add an interaction term between $tailpct_t$ and t, as in Equation 3. The coefficient λ captures the overall trend. If λ_1 is of the same sign as β_1, then the effect of the driving restriction becomes more effective over time.

$$Outcome_t = \beta_0 + \lambda_1 tailpct_t * t + \beta_1 tailpct_t + \beta_{2-5}\, weekday_{2-5,\,t}$$

$$+ \theta_1 t + \theta_{2-12} month_{2-12,t} + \gamma_{1-5} line_{1-5,t} + \gamma_6 taxi_t + \delta weather_t + e_t \tag{3}$$

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[5] We divide that by 365 so that the coefficient is more readable. One unit in t represents one more year, and t is nearly zero on 1/1/2009.

[6] As the data on the use of taxi cover a short period from June 1, 2011 to May 30, 2014, we only control for the event dummies that can be controlled.

5. Estimation

When a car is banned from driving on a particular date, the driver can respond in several ways. Cancelling the trip, moving the trip to another date, taking bus/rail/taxi, using a bicycle or E-bicycle, or walking can reduce car use during the restricted hours of the restricted date. Leaving early and returning late will only shift car driving to the unrestricted hours. In the meantime, a driver can drive the car regardless of the restriction policy. We have data on the ridership of bus, rail and taxi, but we don't have a direct measure on the number of cars being driven. The traffic performance index measures overall traffic conditions, based on which we can infer the use of cars.

5.1 Effect of Driving Restriction on Traffic Performance Index

Table 7 shows the effect of the driving restriction on the morning and evening traffic indices during peak hours. The upper panel regresses the TPIs on *tailpct*, and the lower panel does so on *tailno4*. The first column uses a parsimonious specification and controls for the dummies on days of week, dummies on months, and a linear daily trend. If one more percentage point of cars are allowed to drive, the AM TPI increases by 0.112, which is highly significant (t statistic is 12.75). The second column further controls for the dummies on events and weather. The estimated effect is the same as that in the first column. The third and fourth columns conduct the same exercise for PM TPI. One more percentage point of cars on the road increases PM TPI by around 0.19. As the average TPI is 4.98 in the morning and 6.08 in the evening, a one-unit increase in TPI corresponds to roughly an increase of 0.15 unit of the standard travelling time (the required travelling time in smooth traffic). Assuming 20 percent of cars are banned each day, the driving restriction helps reduce the travelling time by 34% of the standard travelling time in the morning and by 57% in the evening (0.112*20*15%=0.336, 0.19*20*15%=0.57). The lower panel using *tailno4* gives similar conclusions. People may switch to taxi or bus if their cars are restricted. Given that more use of taxis would increase the traffic index, the significant effect of the driving restriction policy on TPI suggests that the driving restriction policy has to be effective in restricting private cars from driving on the road.

The fifth and sixth columns in Table 7 present the results from Equation 3, which include an interaction term between the restriction variable and *t*. In the regression for the morning index, the coefficient on the interaction is -0.001, which is almost zero, while the coefficient for PM TPI is 0.01, significant at the 10% level (t statistic is 1.85). These results are echoed in the lower panel where *tailno4* is used, except that the interaction term for PM TPI becomes significant at the 5% level. The significant interaction term suggests that, as time goes by, the driving restriction policy becomes more effective in affecting the traffic during the evening rush

hours. On the contrary, the morning traffic represents more rigid demand for transport, and the null interaction effect in the morning may indicate that it is difficult to further improve the policy impact when the transportation demand is rigid.

When their cars are banned from driving between 7 a.m. and 8 p.m. on certain dates, will the drivers instead drive cars before or after the restricted hours? We cannot directly test whether drivers made these shifts, but we can estimate how the possible change affects the aggregate traffic congestion. Using hourly data in 2013, we estimate Equation 2 using *tailno4* as the main predictor for each hour separately.[7] Figure 3 plots the coefficients of *tailno4* and their lower and upper bounds at the 95% confidence level. From midnight to 6 a.m., the driving restriction policy has no impact on the traffic index. The impact forms a bi-modal pattern, which starts at 7 a.m., the same as the starting time of the driving restriction, but ends by 10 p.m., two hours beyond 8 p.m., the ending time of the official driving restriction. Therefore, although some drivers may try to circumvent the driving restriction by leaving early and returning late (there should be more of them on dates when numbers other than 4 are banned), their influence on traffic performance is dominated by the direct effect of the restriction.

5.2 Effect of Driving Restriction on Bus and Rail Ridership

Table 8 presents the effect of the driving restriction on the use of bus or rail. The first two columns regress bus ridership as the dependent variable. According to the full specification, the effect is 10,763 fewer bus riders for each percent of cars that are allowed to drive, which is statistically significant at the 1% level. As there are about 4251 thousand cars registered in Beijing, this is roughly one bus rider for every four banned cars (42.51/10.76=3.95). The third and fourth columns show the effect on rail ridership. When more cars are allowed to drive, rail ridership drops too, but the effect is not statistically significant in any of the specifications.

The fifth and sixth columns of Table 8 present the interacting effect between the restriction variables and the daily trend *t*. For bus, the coefficient of the interaction is negative, suggesting that the substitution between cars and bus gets stronger as time goes on. The interaction for rail is positive. However, the coefficient is far from being significant in either case.

There are two puzzles related to the effect on the use of rail. One is that drivers were attracted to bus but not to rail. The other is that the increased rail lines have attracted many more

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[7] As the data are only available for 2013, there is little need to control for the event dummies.

passengers in later years, but their effect is small among those drivers with banned cars. Compared to the bus, rail has advantages in long-distance travelling and is free of traffic congestion. The difference in fares is at most RMB 1.6 and it shouldn't be a consideration for car drivers. However, rail has limited accessibility – the starting point or destination may be far away from a rail station. This limitation may explain the insignificant effect on rail passenger trips. Alternatively, it could also be that those who can conveniently take rail already do so even without the driving restriction.

5.3 Effect of Driving Restriction on the Use of Taxis

The taxi data come from the driving records of 20 taxi cabs from June 1, 2011 to May 30, 2014. One set of outcomes is the number of trips and travelling miles for each taxi at the daily level. As there are 20 cabs on the same date, and the variable on the driving restriction is at the daily level, we cluster the standard errors at the daily level instead of using robust standard errors. Table 9 presents the results. The driving restriction has a strong effect on the number and miles of paid taxi trips. The restriction policy increases the demand for taxis by 2.4 trips and 23 km, assuming 20 percent of cars are banned (0.121*20=2.4, and 1.148*20=22.96). Given that the average number of trips is 23.1 and the average travel distance is 191km per cab each day, the induced trips and distance account for 10% and 12% of the corresponding daily averages, respectively. These results also indicate that the induced taxi trips are not minor trips and they are above the average distance. The fifth and sixth columns present the results for the interaction of the restriction variable and the daily trend, and none of the coefficients are statistically significant.[8]

We can also use the hourly count to show the variation in the effect of the driving restriction on taxi trips across hours. We aggregate the number of trips across the 20 cabs to generate hourly counts. We estimate the coefficient of tailno4 using Equation 2 for each hour separately. Figure 4 plots the estimated coefficients with the lower and upper bounds at the 95% level. The significant impact starts at 7 a.m. and ends at 8 p.m. – the same as the driving restriction period – but the effect is not significant throughout the restricted period.

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[8] The taxi data last for three years only, and the shorter period may also explain the null interaction effect.

5.4 Factors that Generate the Increasing Restriction Effect

Previous subsections show that the driving restriction policy has a stronger effect on PM TPI as time goes on. Given that the impacts on bus, rail and taxi do not experience any significant variation along the daily time trend, one may speculate that the increasing restriction effect on PM TPI is due to the adjustment in using cars only, instead of any change in substitution to other transportation methods. This subsection intends to explore explicitly how various factors influence the effect of the driving restriction policy.

As many events happened during this data period, it is difficult to pin down the exact forces. We adopt simple logic to exclude a factor as a possible explanation if it does not have a significant impact on the immediate channel. For example, if a new rail line does not make rail ridership a better substitute for cars, then it shouldn't explain the stronger effect on PM TPI. We modify Equation 2 by interacting *tailpct* with each of the event dummies. When a new rail line opens, the route and schedule of buses tend to change accordingly. We use the dummy for a rail event to index the related adjustment in buses. The first two columns in Table 10 separately present the coefficients of *tailpct* and their interaction term from each regression, and none of the interactions is statistically significant. The conclusion is the same if *tailno4* is used instead (results are not reported). Therefore, none of the rail, bus or taxi related events can explain the increasing effect of the restriction policy.

The third column of Table 10 changes the dependent variable to PM TPI. Although all the coefficients for the interaction are positive, there are two facts to note: 1) the coefficient for the interaction between *tailpct* and the *combined* event has the largest magnitude, and 2) the coefficients for other interactions are decaying in magnitude as those events become farther away in time from the combined event. These two facts together suggest that the combined event should be the driving force for the more stringent restriction effect.[9] To further examine whether the combined event simply takes up the time trend, we add the two interaction terms together in one regression (the regression results are not reported in the table). The coefficient for *tailpct*combined* changes slightly, from 0.039 to 0.036, while the coefficient for *tailpct*t* drops dramatically, from 0.01 to 0.001, suggesting that the combined event is the leading factor. At the same time, the coefficients of *tailpct*combined* on bus and rail ridership are insignificant and

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[9] The dummies for the various events are highly correlated. Events start at different times, but, once the related dummy variable becomes 1, it remains 1 forever. Therefore, as long as one event has some effect, the dummies for other events may also take some of the effect, because they share some time with the effect. Then the coefficient for the event that truly generates the effect has to have the largest magnitude, and the coefficients for other events should decay when they are farther away from that particular event.

also have an opposite sign from that expected. All the evidence suggests that it is the combination of the car purchase quota and the increasing punishment, rather than the new rail lines, that make the driving restriction more effective in later years.

Evidence from other countries shows that people circumvent the driving restriction by purchasing additional cars. When the regressions have the interaction term *tailpct*combined*, the coefficients for *tailpct* indicate that, before the launch of the car purchase quota, the driving restriction policy was effective in reducing traffic congestion. This effect is coupled with a change in the demand for bus trips.

5.5 Substitution between Car Driving and Other Transit

This subsection discusses the substitution between car driving and other transportation choices. To do so, we have to link the number of cars to the ridership they generate between 7 a.m. to 8 a.m. within the fifth-ring area. During the data period (2009-2014), there were on average 4251 thousand registered cars in Beijing. According to the Fourth City Traffic Survey in Beijing (2010), the proportion of cars running within the fifth ring is 60%; the number of trips by a car per working day is 3.49 on average; the number of passengers in a car per trip is 1.34; and the number of trips from 7 a.m. to 8 p.m. accounts for around 82% of the total number of trips throughout the 24 hours of a day. The driving restriction would suppress ridership of 97.8 thousand for each percentage of cars banned (4251*60%*82%*3.49*1.34*1%=97.8). How many of these 97.8 thousand car passenger trips are transformed to ridership by other methods?

Table 8 shows that there are on average 10.76 thousand fewer bus passenger-trips if the number of driving cars increases by one percent. As one whole trip may take several bus passenger trips if transfers are needed, the substitution between car and bus should be below 11% (10.76/97.8=0.11). Meanwhile, rail only contributes to 2.037 thousand passenger trips (2% of the suppressed car passenger trips), and it is not statistically significant. In total, fewer than 13% of the suppressed car passenger trips have been changed to trips by public transit.

There are about 67 thousand taxis in Beijing, which is unchanged over many years. The proportion of the taxis at work is around 85% per day on average.[10] One taxi may take more than one passenger; we don't have data on the average number of passengers per taxi, so we use 1.34, the average for a car trip, to approximate it. Therefore, for a one percent increase in car

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[10] The Fourth City Traffic Survey in Beijing (2010).

driving, the taxi ridership decreases by 9.16 thousand (67*0.12*1.34*85%=9.16), which is 9.4% of the suppressed car ridership.

6. Conclusion

Given its easy implementation, the driving restriction policy has been popular in many developing countries, like Mexico, Brazil, and China. But how the restriction policy affects transportation choices remains ambiguous. This study explores the daily variation in the volume of driving due to cultural avoidance of license plates ending in the number 4. We have four major findings. First, the driving restriction policy is effective in reducing traffic congestion. Its impact not only covers the regulated period, but also expands two hours after the ending time of the restriction. We don't find any evidence that the restriction policy negatively affects traffic conditions during the un-regulated hours.

Second, the substitution rate from car driving toward public transit is no more than 13%, with bus accounting for the largest share, 11%. Taxis take an additional 9.4% of the suppressed car ridership.

Third, although previous studies argue that the purchase of additional cars accounts for the null effect of the driving restriction in Mexico City, our results suggest that the driving restriction motivated many drivers to take the bus before 2011, while they could still easily get a car license for an additional car.

Fourth, after the launch of the car purchase quota and the more stringent punishment for violating the driving restriction in 2011, the driving restriction exhibits a stronger impact on traffic conditions during the evening peak hours. In the meantime, the substitution toward public transit does not increase, suggesting that, in response to the driving restriction, people are more likely to reschedule or cancel car trips in the long run.

The nearly null response of rail passenger trips to the driving restriction is puzzling. Bus ridership decreases when more cars are allowed to drive. This suggests that there is demand for public transit when cars are banned, but this demand only goes to bus rather than rail. Understanding this puzzle will help policy makers further improve the effectiveness of the driving restriction and better design the infrastructure of public transportation. Given the data limitation, we leave this for future study.

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Tables and Figures

Table 1. Arrangement of Tail Number Restriction Policy

Starting	Ending	Mon.	Tues.	Wed.	Thur.	Fri.	Holidays
10/11/2008	11/10/2008	1 & 6	2 & 7	3 & 8	4 & 9	5 & 0	
11/11/2008	12/10/2008	2 & 7	3 & 8	4 & 9	5 & 0	1 & 6	
12/11/2008	1/10/2009	3 & 8	4 & 9	5 & 0	1 & 6	2 & 7	12/29/2008-1/1/2009
1/11/2009	2/10/2009	4 & 9	5 & 0	1 & 6	2 & 7	3 & 8	2/6-2/12
2/11/2009	3/10/2009	5 & 0	1 & 6	2 & 7	3 & 8	4 & 9	
3/11/2009	4/10/2009	1 & 6	2 & 7	3 & 8	4 & 9	5 & 0	4/4-4/6
4/11/2009	7/10/2009	5 & 0	1 & 6	2 & 7	3 & 8	4 & 9	5/1-5/3, 6/7-6/9
7/11/2009	10/9/2009	4 & 9	5 & 0	1 & 6	2 & 7	3 & 8	9/13-9/15, 9/29-10/5
10/10/2009	1/8/2010	3 & 8	4 & 9	5 & 0	1 & 6	2 & 7	1/1-1/3
1/9/2010	4/10/2010	2 & 7	3 & 8	4 & 9	5 & 0	1 & 6	2/13-2/19, 4/3-4/5
4/11/2010	7/10/2010	1 & 6	2 & 7	3 & 8	4 & 9	5 & 0	5/1-5/3, 6/14-6/16
7/11/2010	10/9/2010	5 & 0	1 & 6	2 & 7	3 & 8	4 & 9	9/22-9/24, 10/1-10/7
10/10/2010	1/8/2011	4 & 9	5 & 0	1 & 6	2 & 7	3 & 8	1/1-1/3
1/9/2011	4/10/2011	3 & 8	4 & 9	5 & 0	1 & 6	2 & 7	2/2-2/7, 4/3-4/5
4/11/2011	7/9/2011	2 & 7	3 & 8	4 & 9	5 & 0	1 & 6	4/30-5/2, 6/4-6/6
7/10/2011	10/8/2011	1 & 6	2 & 7	3 & 8	4 & 9	5 & 0	9/10-9/12,10/1-10/7
10/9/2011	1/7/2012	5 & 0	1 & 6	2 & 7	3 & 8	4 & 9	1/1-1/3
1/8/2012	4/10/2012	4 & 9	5 & 0	1 & 6	2 & 7	3 & 8	1/22-1/28,4/2-4/4
4/11/2012	7/10/2012	3 & 8	4 & 9	5 & 0	1 & 6	2 & 7	4/29-5/1,6/22-6/24
7/11/2012	10/9/2012	2 & 7	3 & 8	4 & 9	5 & 0	1 & 6	9/30-10/7
10/10/2012	1/8/2013	1 & 6	2 & 7	3 & 8	4 & 9	5 & 0	1/1-1/3
1/9/2013	4/7/2013	5 & 0	1 & 6	2 & 7	3 & 8	4 & 9	2/9-2/15,4/4-4/6
4/8/2013	7/6/2013	4 & 9	5 & 0	1 & 6	2 & 7	3 & 8	4/29-5/1,6/10-6/12
7/7/2013	10/5/2013	3 & 8	4 & 9	5 & 0	1 & 6	2 & 7	9/19-9/21,10/1-10/7
10/6/2013	1/4/2014	2 & 7	3 & 8	4 & 9	5 & 0	1 & 6	12/30/2013-1/1/2014
1/5/2014	4/11/2014	1 & 6	2 & 7	3 & 8	4 & 9	5 & 0	1/30-2/5,4/5-4/7

Table 2. Percentage of Cars with Different Ending Numbers

Tail no.	2009	2010	2011	2012	2013
1	10.0%	9.9%	9.9%	9.9%	9.9%
2	10.2%	9.9%	9.9%	9.9%	9.9%
3	9.9%	9.7%	9.6%	9.6%	9.6%
4	2.8%	2.3%	2.2%	1.9%	1.7%
5	10.4%	10.4%	10.5%	10.6%	10.7%
6	11.7%	12.1%	12.3%	12.3%	12.3%
7	10.1%	10.1%	10.2%	10.3%	10.4%
8	12.7%	13.0%	12.9%	12.9%	12.8%
9	11.6%	12.1%	12.2%	12.3%	12.2%
0	10.6%	10.5%	10.5%	10.5%	10.6%
1 & 6	21.7%	22.0%	22.1%	22.2%	22.2%
2 & 7	20.3%	20.1%	20.0%	20.1%	20.3%
3 & 8	22.6%	22.6%	22.5%	22.4%	22.3%
4 & 9	14.4%	14.4%	14.4%	14.1%	13.9%
5 & 0	21.0%	20.9%	21.0%	21.1%	21.3%

Note: All the data are as of December 31 of that year, except in 2013, for which the data are as of 1/31/2014. Car plates ending in letters are in the category "0."

Table 3. Interpretation of Traffic Performance Index

Index	Category	Travel time
0~2	Smooth	1 unit
2~4	Basically smooth	1.2-1.5 units
4~6	Slightly congested	1.5-1.8 units
6~8	Moderately congested	1.8-2.1 units
8~10	Seriously congested	> 2.1 units

Table 4. Summary Statistics

Variable	Obs	Mean	Std	Min	Max
Percentage of cars allowed on road	1,241	79.978	2.992	77.37	86.06
Whether 4 is restricted	1,241	0.197	0.398	0	1
AM TPI	1,234	4.978	1.269	1.9	9.4
PM TPI	1,232	6.075	1.545	2	10
Hourly TPI	5690	2.585	1.848	0.613	9.123
Bus passenger-trips (k)	1,222	14483	680	10728	16497
Subway passenger-trips (k)	1,237	6934	1990	3240	11559
Taxi, number of trips	12,457	23.11	12.30	1	102
Taxi, miles of trips	12,457	191.01	94.19	0.1	835.8
Taxi, hourly number of trips	16142	17.834	9.487	1	53
Rain (0.1mm)	1,241	15.472	67.116	0	842
Temperature (0.1℃)	1,241	138.39	112.44	-125	345
Humidity (1%)	1,241	51.168	19.907	9	97
Barometric pressure (0.1hPa)	1,241	10118	102.85	9897	10371
Sunshine (0.1h)	1,241	66.961	40.766	0	141
Max wind speed (0.1m/s)	1,241	49.970	17.773	17	119

Note: Hourly TPI data cover the year 2013; the coverage period for taxi data is from June 1, 2011 to May 30, 2014. For all other variables, the period is from Jan. 1, 2009 to May 30, 2014.

Table 5. List of Important Events and Variables

Start time	Events	Variables
4/11/2009	The restricted period was changed from 6-21 to 7-20.	-
9/28/2009	Rail Line 4	line4
12/30/2010	5 new rail lines, Rail Line 15, Changping, Daxing, Fangshan, Yezhuang	Combined
1/1/2011	Car purchase quota	
1/1/2011	Punishment for violating the driving restriction change from 100 yuan per day to 100 yuan per 3 hours	
12/30/2011	Rail Line 9	line9
12/30/2012	Rail Line 6	line6
5/5/2013	Rail Line 14	line14

Notes: There are very few data points before 4/11/2009, so we skip that event. The variable *combined* takes the value 1 starting from 1/1/2011.

Table 6. Testing for the Exogeneity of the Restriction Variables

	Rain	Temperature	Humidity	Pressure	Sunshine	Wind
Regression using *tailpct*						
Tailpct	-0.497	-0.042	0.004	-0.070	-0.061	-0.047
	(0.573)	(1.073)	(0.185)	(0.977)	(0.392)	(0.162)
Regression using *tailno4*						
tailno4	-1.920	-0.750	0.362	-1.408	-0.895	-0.392
	(4.123)	(8.065)	(1.390)	(7.343)	(2.947)	(1.213)
Weekday fixed effect	Y	Y	Y	Y	Y	Y
N	1241	1241	1241	1241	1241	1241

Note: Twelve regressions are conducted in total for this table. Robust s.e. are in parentheses.

* significant at 10 percent; ** significant at 5 percent; *** significant at 1 percent

Table 7. Effect of Driving Restriction on Traffic Performance Index (TPI)

	(1) AM TPI	(2) AM TPI	(3) PM TPI	(4) PM TPI	(5) AM TPI	(6) PM TPI
Regression using *tailpct*						
Tailpct	0.112***	0.112***	0.192***	0.191***	0.116***	0.162***
	(0.009)	(0.008)	(0.010)	(0.009)	(0.018)	(0.019)
*tailpct*t*					-0.001	0.010*
					(0.005)	(0.006)
Regression using *tailno4*						
tailno4	0.806***	0.805***	1.355***	1.345***	0.793***	1.064***
	(0.066)	(0.057)	(0.075)	(0.067)	(0.132)	(0.137)
*tailno4*t*					0.005	0.104**
					(0.039)	(0.040)
Weekday fixed effect	Y	Y	Y	Y	Y	Y
Monthly fixed effect	Y	Y	Y	Y	Y	Y
Linear daily trend *t*	Y	Y	Y	Y	Y	Y
Event effects		Y		Y	Y	Y
Weather variables		Y		Y	Y	Y
N	1234	1234	1232	1232	1234	1232

Note: Twelve regressions are conducted in total for this table. Robust s.e. are in parentheses.

* significant at 10 percent; ** significant at 5 percent; *** significant at 1 percent

Table 8. Effect of Driving Restriction on the Use of Bus and Rail

	(1) Bus	(2) Bus	(3) Rail	(4) Rail	(5) Bus	(6) Rail
Regression using *tailpct*						
Tailpct	-10.485**	-10.763***	-2.050	-2.037	-9.519	-2.578
	(4.911)	(3.929)	(4.367)	(2.175)	(9.701)	(4.178)
*tailpct*t*					-0.451	0.196
					(2.851)	(1.492)
Regression using *tailno4*						
tailno4	-94.902***	-92.000***	-19.568	-19.746	-87.541	-25.707
	(36.754)	(29.221)	(32.334)	(16.104)	(71.118)	(30.416)
*tailno4*t*					-1.661	2.213
					(21.288)	(11.346)
Weekday fixed effect	Y	Y	Y	Y	Y	Y
Monthly fixed effect	Y	Y	Y	Y	Y	Y
Linear daily trend *t*	Y	Y	Y	Y	Y	Y
Event effects		Y		Y	Y	Y
Weather variables		Y		Y	Y	Y
N	1222	1222	1237	1237	1222	1237

Note: Twelve regressions are conducted in total for this table. Robust s.e. are in parentheses.
* significant at 10 percent; ** significant at 5 percent; *** significant at 1 percent

Table 9. Effect of Driving Restriction on the Use of Taxis

	(1) Trips	(2) Trips	(3) Distance	(4) Distance	(5) Trips	(6) Distance
Regression using *tailpct*						
Tailpct	-0.114***	-0.121***	-1.102***	-1.148***	-0.208*	-1.578*
	(0.028)	(0.026)	(0.218)	(0.195)	(0.125)	(0.935)
*tailpct*t*					0.022	0.110
					(0.029)	(0.223)
Regression using *tailno4*						
tailno4	-0.756***	-0.806***	-7.778***	-8.089***	-1.541	-11.786*
	(0.214)	(0.196)	(1.668)	(1.491)	(0.948)	(7.056)
*tailno4*t*					0.189	0.951
					(0.223)	(1.696)
Weekday fixed effect	Y	Y	Y	Y	Y	Y
Monthly fixed effect	Y	Y	Y	Y	Y	Y
Linear daily trend *t*	Y	Y	Y	Y	Y	Y
Event effects		Y		Y	Y	Y
Weather variables		Y		Y	Y	Y
N	12457	12457	12457	12457	12457	12457

Note: Twelve regressions are conducted in total for this table. Clustered s.e. at the daily level are in parentheses.

* significant at 10 percent; ** significant at 5 percent; *** significant at 1 percent

Table 10. The Interacting Effect of Various Events with the Driving Restriction Policy

	Bus	Rail	PM TPI
Tailpct	5.196	-2.114	0.167***
	(15.715)	(5.729)	(0.029)
*tailpct*line4*	-18.391	0.089	0.028
	(16.215)	(6.237)	(0.030)
tailpct	-14.878**	-4.802	0.166***
	(7.506)	(3.370)	(0.016)
*tailpct*combined*	6.510	4.345	0.039**
	(8.758)	(4.422)	(0.019)
tailpct	-8.314	-1.107	0.178***
	(5.680)	(2.517)	(0.013)
*tailpct*line9*	-5.443	-2.034	0.028
	(7.748)	(4.539)	(0.017)
tailpct	-10.259**	-2.094	0.185***
	(4.867)	(2.166)	(0.011)
*tailpct*line6*	-1.836	0.217	0.022
	(8.186)	(6.019)	(0.017)
tailpct	-9.949**	-1.533	0.188***
	(4.618)	(2.320)	(0.010)
*tailpct*line14*	-3.696	-2.368	0.013
	(8.462)	(6.025)	(0.019)
	Trips	Distance	PM TPI
tailpct	-0.122***	-1.119***	0.187***
	(0.034)	(0.255)	(0.010)
*tailpct*taxi*	0.005	-0.088	0.019
	(0.048)	(0.375)	(0.020)

Note: Eighteen regressions are conducted in total for this table. Robust s.e. are in parentheses. All the regressions include weekday fixed effect, monthly fixed effect, linear daily trend, event effects, weather and the restriction variable *tailpct*.

* significant at 10 percent; ** significant at 5 percent; *** significant at 1 percent

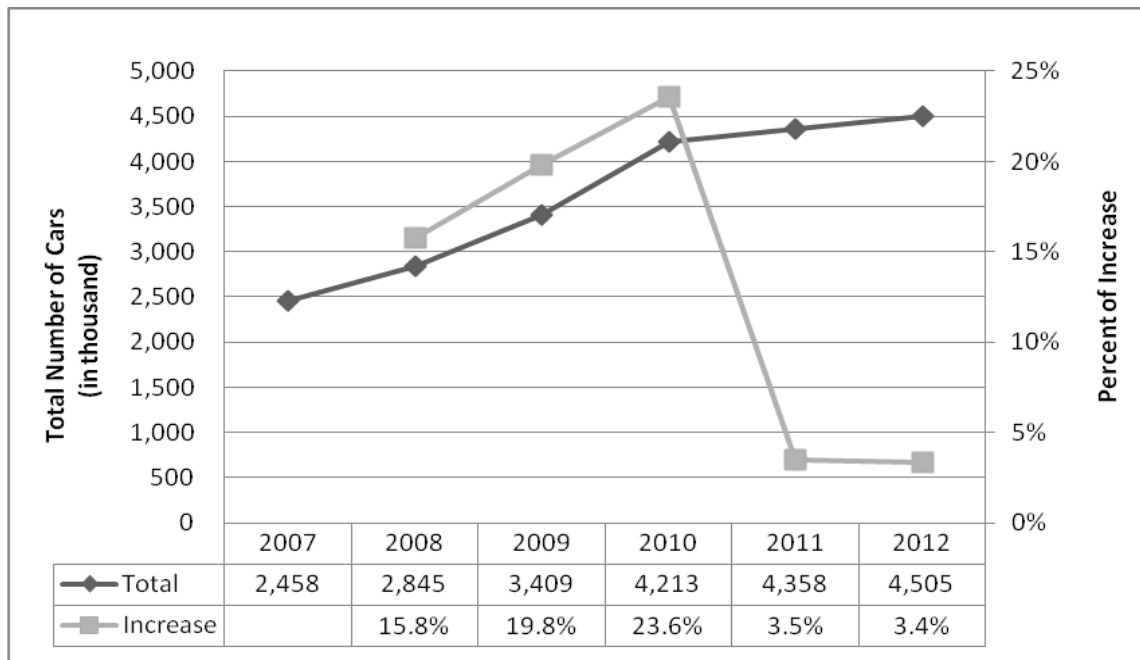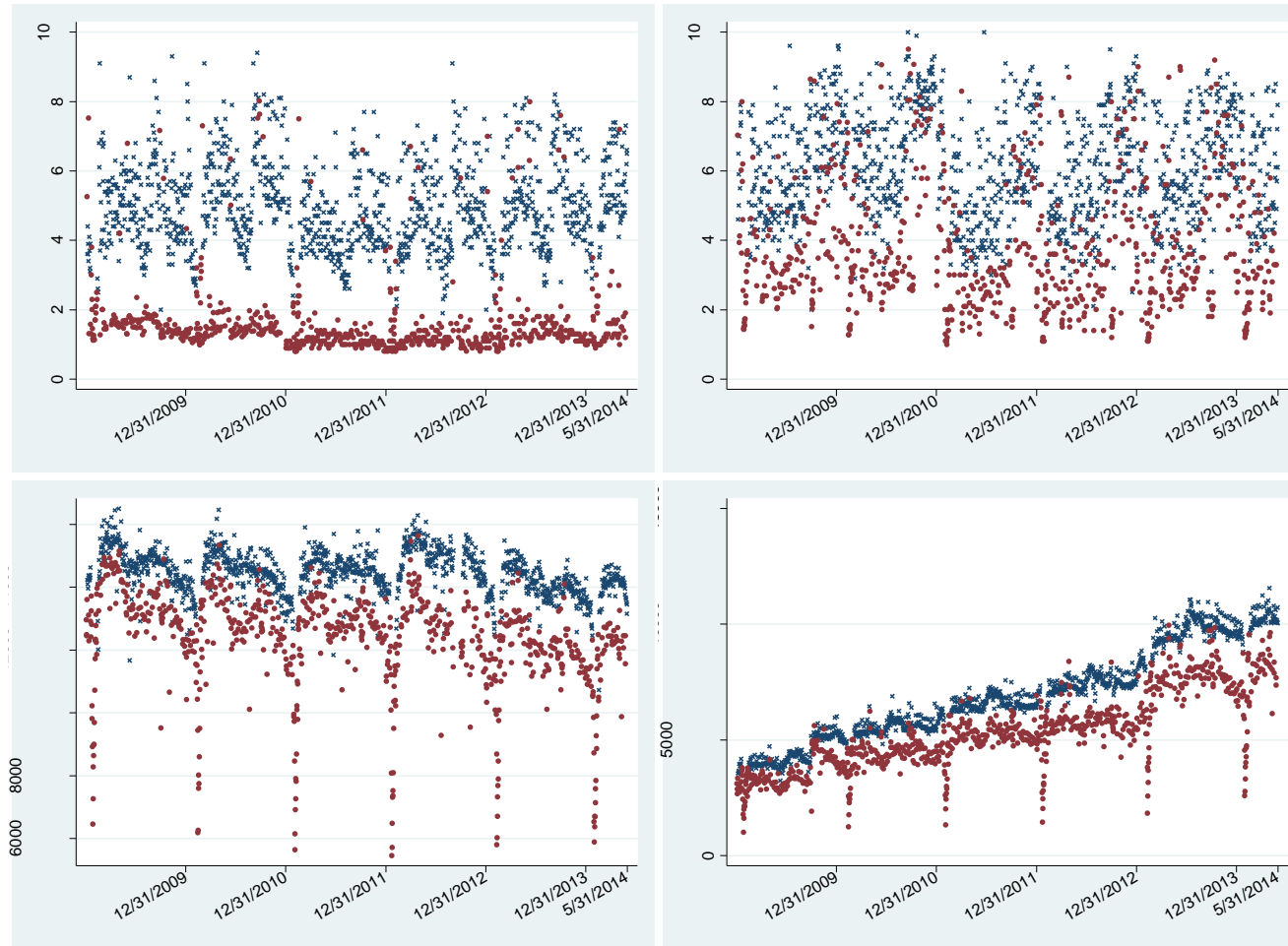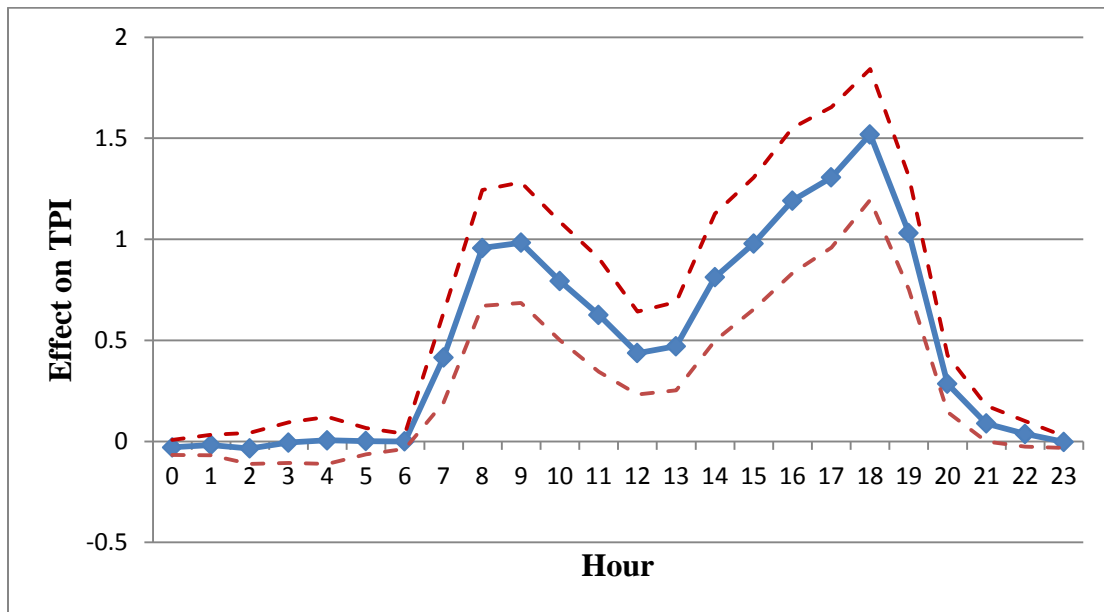**Figure 1. Total Number and Percentage Increase of Registered Cars in Beijing**

	2007	2008	2009	2010	2011	2012
Total	2,458	2,845	3,409	4,213	4,358	4,505
Increase		15.8%	19.8%	23.6%	3.5%	3.4%

Figure 2. Traffic Performance Index (TPI), Bus and Rail Ridership by Date

Note: the symbol "x" is for regular dates and "." is for irregular dates.

Figure 3. Effect of Driving Restriction on TPI by Hours

Figure 4. Effect of Driving Restriction on Taxi Ridership by Hours