The Effect of Driving Restrictions on Travel Behavior in Beijing

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Abstract:

This article measures the effect of Beijing's driving restrictions on individual travel behavior using 2010 Beijing Household Travel Survey data. Driving restrictions decrease the auto use, however, with the effect lower than expectation. Evidence from trip frequency indicates that the adjustment in travel behaviors varies across individuals: for example, female, high-income drivers who live in the south of the Beijing central city tend to decrease auto use more facing restrictions. Drivers also make inter-temporal adjustments in trip making, especially within a 3-day time window. We also provide evidence of the uneven restrictions, that is, high traffic flow in the 4&9 restricted days, as well as how non-drivers decrease their trip frequency in such days.

Keywords: driving restriction; modal split; trip frequency; Beijing

1. Introduction

Driving restrictions, mainly as a way to combat air pollution, have been implemented in cities around the world for decades[1]. For example, in 1989 the Mexico City government introduced a "One Day without a Car" program that bans vehicle use one weekday per week (20% of vehicles off the road) by the plate license number. The restriction would be extended to 50% of vehicles when the air pollution level is high.

However, the limited empirical studies have doubted the effectiveness of such policies. Using a regression discontinuity design, Davis (2008) finds no evidence that the program in Mexico City has improved air quality, on the basis of the air pollution records from the monitoring stations. Eskeland and Feyzioglu (1997), who examine gasoline sales and vehicle ownership in Mexico City, propose that this is due to the fact that many households have purchased additional cars, most of them old, high-emission cars[2]. Davis (2008) further confirms this by revisiting the evidence presented by Eskeland and Feyzioglu (1997).

It is possible that driving restrictions improve the air quality only in the short run since it takes a while for households to adapt to the policy (Davis, 2008). Salas (2010) shows that the program in Mexico City has reduced air pollution at the beginning, followed by a gradual increase in pollutant concentration, by slightly changing the methodology used by Davis (2008). Gallego et al. (2011), who examine the driving restriction in Mexico City and the public transit reform in Santiago, obtain the similar result: an immediate reduction in CO concentrations by 11%, followed by a 13% increase in the long run in Mexico City. Both Salas (2010) and Gallego et al. (2011) indicate that the adaptation takes around 9-11 months.

The important link between driving restrictions and air quality is traffic flow, i.e., the aggregate vehicle use. Using the hourly traffic flow between April and August of 2008 in Santiago, Grange and Troncoso (2011) show that the pre-emergency restriction, which is non-regular and contingent upon the air pollution level, decreases traffic flow by 5.5%, much lower than 20%, the ratio of vehicles restricted for use. This difference could be explained by the ownership of more than one car, driving during unrestricted hours (before 7:30am or after 9:30pm in this case), and

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[1] Most of them are Latin American cities, including Buenos Aires, Argentina; Caracas, Venezuela; Mexico city, Mexico; Sao Paulo, Brazil; Bogota and Medellin, Columbia; and Managua, Nicaragua. For a brief review on related policies in these cities, see Grange and Troncoso (2011).

[2] As a traditionally exporter of used vehicles to the rest of the country, Mexico City became an importer since the implementation of the program (Eskeland and Feyzioglu, 1997).

simply noncompliance. They also suggest that drivers tend to use the metro instead of the bus when car use is restricted, similarly using the ridership data of metro and bus.

Although the above studies have made serious attempts to evaluate the effect of driving restrictions, what is missing is the individual response to such policies in terms of travel behavior and daily activities. For example, what mode will a driver turn to in the day his/her car is restricted for use? Who tends to decrease his/her daily trip frequency more facing the restriction? Without such information, it is hard to derive the welfare effects of driving restrictions on different population groups. One exception is the study by Viard and Fu (2011), who examine the relationship between driving restriction and work day length indirectly using hourly TV viewership across workers with and without discretionary work time in Beijing, China.

This article measures the effect of driving restrictions on individual travel behavior using 2010 Beijing Household Travel Survey data. During 2008 Olympics, the Beijing municipal government implemented driving restrictions for the purpose of alleviating both air pollution and travel congestion, which ban half of the vehicles every day by the last digit of license plates (hereafter 50%-off restrictions). The restrictions were then relaxed by preventing driving one weekday per week, but remain effective till now (hereafter 20%-off restrictions). Viard and Fu (2011) and Lin et al. (2011) use the same method as Davis (2008) to examine whether such a policy has improved air quality[3]. The former study shows that 50%-off restrictions reduce PM_{10} concentrations by 19% and 20%-off restrictions by 8%, while the latter finds a 38% reduction for 50%-off restrictions and no significant effect for 20%-off restrictions. An evaluation report by Beijing Transportation Research Center indicates that 20% restrictions increase the travel speed by around 15% during peak hours and decrease daily traffic flow on main roads by 2.8%-4.1%, by directly comparing traffic across periods with (October 11, 2008 to February 28, 2009) and without restrictions (October to November, 2007)[4].

In this study, we focus on only the effect of the 20%-off restrictions: travel behaviors are compared across drivers in the day when their car use is restricted and those in their unrestricted day, which is guaranteed by the fact that driving restrictions can be taken as randomized social experiments. 2010 Beijing Household Travel Survey data provides the one-day travel diary of

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[3] Viard and Fu (2011) use the daily air pollution index (API) of Beijing from January 1, 2007 to December 31, 2009, while Lin et al. use the API data between July 20, 2007 to October 31, 2009.

[4] A summary is available at http://www.bjjtw.gov.cn/gzdt/dtxx/200904/t20090402_32864.htm (in Chinese), accessed on June 8, 2012.

46,900 households in the whole Beijing City and the last digit of plate license for every vehicle these households own. The survey was taken during September 8 to October 31, 2010, with households surveyed in different days, which helps control for the weekly variation in travel pattern. According to our knowledge, this is one of the first attempts to report individual behavioral responses to driving restrictions. Although we cannot evaluate the benefits of driving restrictions with such cross-sectional data, the analysis sheds light on the compliance costs of driving restrictions by examining how individuals make adjustments, and specially inter-temporal adjustments, on their travel behaviors and how the adjustments vary across population groups. One major criticism over driving restrictions, in contrast to market-based measures such as fuel tax and congestion toll, is the neglect of the variation in willingness to pay for car use across individuals and the variation for an individual within a week (Eskeland and Feyzioglu, 1997).

We find that as expected, the auto share of trips for drivers in their restricted day is lower by about 10% than that for those in their unrestricted day. The comparison of modal split also indicates that some drivers switch to bus, bicycle, and taxi when their car use is restricted. However, due to the facts mentioned earlier, e.g., having access to other cars unreported, the auto share of trips is still higher than 50% for drivers in their restricted day. This indicates that the effect of driving restrictions on auto use might be lower than what the government has expected.

Driving restrictions tend to decrease a driver's trip frequency by limiting his/her mode choice set and thus increasing his/her transportation cost. Here, a driver's decision-making process is decomposed into two steps: i) making at least one trip or just staying at home in the survey day, which is estimated using a binary logit model; and ii) the number of trips given making at least one trip, estimated using an OLS model. We first investigate the effect on auto trip frequency since it is closely related to travel congestion and air pollution. The estimates show that driving restrictions significantly decrease the possibility of making at least one auto trip for drivers in their restricted day by almost 9%, compared with those in their unrestricted day. However, it is hard to say whether there is any inter-temporal adjustment on travel behaviors. Further, female, high-income drivers who live in the south of the Beijing central city (areas within the 5th ring road) tend to decrease the possibility of auto use more when their car use is restricted, which reveals the difference in willingness to pay for car use across individuals. The estimates on the number of auto trips indicate that there is kind of inter-temporal adjustment in auto use in a 3-day time window. The similar analysis is also done for work trips and non-work trips by auto, respectively.

We then examine the effect of driving restrictions on (all) trip frequency. The estimates provide evidence of inter-temporal adjustments on travel behaviors: a driver is more likely to go out of home in the day that is just before or after his/her restricted day than other unrestricted days. Middle-income drivers have higher possibility to stay at home, possibly due to both their flexibility in rescheduling travels/activities and their reluctance to use alternative modes. Female drivers are more affected by driving restrictions in terms of non-work trips, which is consistent with our expectations.

In addition, driving restrictions are not uniform within a week because of a special phenomenon in China that people dislike the plate license number ending with "4". Therefore, on days when vehicles with last digit as 4&9 are restricted, there would be more traffic flow. This unnecessarily increases compliance costs of driving restrictions because people also need consider the uneven distribution of traffic flow within a week when adjusting their travel behaviors. We expect that people tend to decrease their trip frequency in the 4&9 restricted day. The fact that 2010 Survey spans two periods in which 4&9 are restricted in different weekdays eases the identification. The estimates show that this is not true for drivers but true for non-drivers[5]. This could be explained by i) less freedom for drivers given the auto reliance and driving restrictions and ii) lower elasticity of auto travel demand to traffic volume. This result indicates that driving restrictions in Beijing are implemented at the cost of even non-drivers, who are supposed to benefit from such policies without paying anything.

The rest of this article is organized as follows. Section 2 summarizes driving restrictions in Beijing. Section 3 gives a brief introduction to 2010 Survey data. In Section 4 modal split is examined to show the mode choice of drivers facing restrictions. In Section 5 we estimate the effect of driving restrictions on auto trip frequency and total trip frequency. The "4&9" effect is addressed in Section 6. Section 7 concludes.

2. Driving restrictions in Beijing

During 2008 Beijing Olympics, the Beijing municipal government implemented driving restrictions for the purpose of alleviating both air pollution and travel congestion. The restrictions

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[5] The fact that 2010 Survey spans two periods in which 4&9 are restricted in different weekdays eases the identification, which is introduced in more details in Section 2.

banned half of the vehicles off the road every day (except 0am to 3am) by the last digit of license plates (odd or even), from July 20 to September 20, 2008. The government relaxed driving restrictions after Olympics. New restrictions, initiated since October 11, 2008, prevent driving one weekday per week (20%-off every weekday). The 20%-off restrictions apply to areas within and including the 5th ring road (Figure 1), and between 6am and 9pm. On April 11, 2009, driving restrictions were further relaxed a little, applying between 7am and 8pm and not including the 5th ring road due to moderate traffic flows on it, and remain effective till now. In this study, we investigate individual behavior responses to newest restrictions since the survey records individual travel behaviors in only 2010. The main focus is on households who live within the restriction area. For simplicity, we refer to areas within the 5th ring road as the Beijing central city.

[Insert Figure 1 around here]

In each weekday, two last digits out of ten of plate licenses are restricted, following the pairs of 0&5, 1&6, 2&7, 3&8, and 4&9, which have been the same throughout. The rule that assigns these digit pairs to weekdays changes initially every month, while after April 11, 2009, every thirteen months. Driving restrictions apply to all private and public vehicles except police cars, fire trucks, ambulances, buses, taxis, and other vehicles authorized by the government.

At the end of 2010, there are about 4.8 million registered vehicles in Beijing[6], which means that on average nearly one million vehicles are restricted for use every weekday. However, driving restrictions are not uniform within a week because of a special phenomenon in China that people dislike the plate license number ending with "4". Out of 14,625 vehicles[7] used by all sampled households in 2010 Beijing Survey, there are only 2.4% with "4" as last license digit, and thus, only 13.6% with "4" or "9" as last digit (Figure 2), much lower than that with other digit pairs. Therefore, we expect higher traffic volume in the 4&9 restricted day, which is actually widely perceived by the public and reported on various media. In this study, we examine how people make inter-temporal adjustments on their travel behaviors in face of this.

[Insert Figure 2 around here]

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[6] This is cited from the website of Beijing Traffic Management Bureau, at http://www.bjjtgl.gov.cn/publish/portal0/tab118/.

[7] The government or firm provided vehicles account for less than 5%. In the following we do not make any differentiation between public and private vehicles since driving restrictions treat them equally.

3. Data

The Beijing municipal government has organized four large-scale household travel surveys respectively in 1986, 2000, 2005 and 2010. The recent 2010 Survey adopts a multistage sampling strategy with a target of 1% sampling rate. 1,085 TAZs (traffic analysis zones) out of 1,911 in the whole Beijing City are finally selected. In each TAZ, 10 to 50 households are selected to take a face-to-face interview. The final sample size is 46,900 households (116,142 persons) in the whole city.

2010 Survey data provides the one-day travel diary of all respondents, household information including household structure, income, and residential location at the TAZ level, as well as personal information including gender, age, household role, job, etc. Also, for every vehicle these households use, no matter public or private, the main user is identified and the last digit of plate license is recorded, which tells us whether the vehicle is restricted for use in the survey day. The survey was taken during September 8 to October 31, 2010, with households surveyed in different days, which helps control for the weekly variation in travel pattern.

For the purpose of investigating the effect of driving restrictions on trip frequency, we generate a trip dataset on basis of the original trip segment dataset. Here a trip is defined as traveling between two anchor destinations with a specific purpose excluding transfer. In total there are 253,584 trips in 2010 Survey data. The trip mode is identified as the mode of the trip segment that has longest duration (we have no information on distance except the origin-TAZ and the destination-TAZ). In case there are two or more segments that have same, longest duration, we choose the mode of highest mobility. For example, the mobility of car is higher than that of bus. Using other methods in identifying the main mode would not affect the main results in this study, because 96,370 out of 96,389 auto trip segments are identified as a single auto trip with no combination of other modes, due to lack of P&R (park and ride) facilities in Beijing.

Among 46,900 sampled households, 26.7% (12,503 households) have one vehicle, and 2.2% (1,034 households) have at least two vehicles. In this study, we mainly focus on weekday travel behaviors of drivers in households who live within the 5^{th} ring road and have only one vehicle, no matter public or private. 5,123 drivers with complete information are finally selected according to such criteria. Summary statistics are presented in Table 1. Nearly 80% of these drivers are male, their average age is 40, and 14% of them have at least a kid of age 6 to 12. Among these drivers, 34% are classified as low-income (annual household income less than 50,000 RMB, or $7,550 by the exchange rate at the end of 2010), 47% as middle-income (income between 50,000 RMB and 100,000 RMB, or $15,100), and 14% as high-income (income greater than 100,000 RMB). Only 12% of them have not any public transit pass, using which a bus rider could enjoy a 60% off fare.

[Insert Table 1 around here]

To control for the geographic variation in travel behaviors and examine the location-specific effect of driving restrictions, we also construct several location variables on basis of the TAZ in which a driver resides. The Beijing City is usually divided into three regions by administrative boundaries (Figure 1): downtown (two innermost districts, Dongcheng and Xicheng), suburb (four districts adjacent to downtown, Chaoyang, Haidian, Fengtai, and Shijingshan), and exurb (other ten districts far away from urban center). 31% of these drivers live in downtown, 65% in suburb, and only 4% in exurb, since we focus on drivers who live within the 5^{th} ring road. One well-known fact about Beijing is the insufficient provision of public facilities and infrastructure such as public transit in the south, with Chang'an Street as the boundary. Of these drivers, slightly more than half live in the north. In addition, we measure the air distance to the nearest metro station from each driver's residence (centroid of the TAZ in which he/she lives) to control for the effect of metro availability on individual trip frequency. For this variable, there might be measurement error since the average area of all TAZs within the 5^{th} ring road is about $1km^2$.

For these drivers, their survey days are almost uniformly distributed within a week. Linking the last plate license digit of their cars to the survey day, we find that about 1/5 of these drivers (990 out of 5,123) cannot use their cars in the survey day. And for 18% (17%) of these drivers, the survey day is just one day before (after) their restricted day. This is used to test whether there is some form of inter-temporal adjustment on travel behaviors. Several interactive variables, the product of the "restriction" dummy and some demographic or location variable such as whether a driver is of high-income, are calculated to investigate the different effects of driving restrictions on people of different features or in different locations, that is, how the adjustments vary across population groups.

On average, each driver makes 2.56 trips, including 0.82 work trips and 0.74 non-work trips, in each weekday, with the effect of driving restrictions included. Only 10% of them make no trips in the survey day, while 38% of them have no work trips and 53% have no non-work trips. Here a non-work trip is defined as a trip of any purpose except work, business or back home. In terms of auto trips, each driver makes 1.61 auto trips in each weekday, of which there are 0.53 work trips and 0.39 non-work trips. 40% of these drivers have no auto trips in the survey day, including both drivers in their restricted day and those in their unrestricted day. 51% of them have no auto work trips and 77% have no auto non-work trips. The above figures also show that work travel still has a dominant share of overall travel in Beijing.

The 2010 Survey spans two periods with different rules that assign digit pairs to weekdays (Table 2). In the first period, September 8 to October 9, 2010, vehicles with last digit as 4&9 are restricted on Friday, while in the second period, October 10 to 31, 2010, these same vehicles are restricted on Monday. This provides an opportunity for examining how people adjust their travel behaviors in response to the relatively high traffic flow in the 4&9 restricted day, after controlling for the weekly variation in travel behaviors.

[Insert Table 2 around here]

4. Mode choice under restrictions

Modal split on weekdays for two groups of drivers, those in their restricted day and those in their unrestricted day, is presented in Table 3. As expected, the auto share of trips for drivers in their restricted day (54.7%) is lower by about 10% than that for those in their unrestricted day (64.5%). For all trips of these drivers, we also estimate a binary logit model on whether a trip is made by auto. The estimation results show that driving restrictions significantly decrease the possibility of auto use (z value -9.31, significant at 0.01 level) from 64.9% to 54.6% for an "average" trip, with gender, age, household structure, income, and weekday dummies controlled for.

[Insert Table 3 around here]

The comparison of modal split indicates that some drivers switch to bus, bicycle, and taxi when their car use is restricted. Compared with that for drivers in their unrestricted day, the bus share of trips for drivers with their car use restricted is higher by about 4%, and the shares of bicycle and taxi higher by less than 2%. Such kinds of modal switch are just what the government has expected when issuing driving restrictions.

However, modal split also shows that even for drivers in the survey day when their car use is restricted, the auto share of trips is still higher than 50%. Of total 1,346 auto trips made by them, 13% (175 trips) are by carpool (60 trips), out of the 5th ring road (9 trips), or before 7am or after 8pm (113 trips). The other trips could mainly be explained by having access to additional cars, e.g., rents a car, using firm or government provided cars unreported in 2010 Survey, or borrowing cars from parents or relatives who live nearby and possibly have been retired. There might also be simply noncompliance due to the not very high fine at that time (100 RMB, about 15$ per day)[8]. However, we cannot differentiate these two cases from 2010 Survey data, and there is no official data on the noncompliance ratio in 2010. In all, of 990 drivers surveyed in their restricted day, nearly half (436 drivers) have at least one auto trip that could not be explained by carpooling, driving out of restricted areas, or out of restricted hours. This surprisingly high ratio indicates that the effect of driving restrictions on auto use might not be as high as what the government has expected, at least in 2010. We investigate who is more likely to stick to auto use when his/her car use is restricted in Section 5.

We make a similar analysis for households that own two vehicles and live within the 5th ring road, which are classified into two groups: households with one car restricted in the survey day, and those with both cars unrestricted. The comparison of modal split shows that it is the former has a higher auto share of all trips (64.3%, while 61.9% for the latter). Looking at trip purposes, we find that the former has much more trips with purpose of "drop off/ pick up" (20.4%, and 14.9% for the latter), since the unrestricted car now need serve the whole family. These figures lend support to the previous idea that the adaptation to the policy such as buying additional cars would neutralize the effect of driving restrictions in the long run, as what has happened in Mexico City. However, such a way of adaptation has more or less been ruled out in Beijing by a strict car registration lottery program implemented since January 1, 2011[9].

5. Trip frequency

People choose to go out only when the net utility in doing so, that is, the positive utility from the activity at destination minus, in most cases, the negative utility from transportation, is greater than the utility from outside option- staying at home or elsewhere. Therefore, driving restrictions tend to decrease a driver's trip frequency by limiting his/her mode choice set and thus increasing his/her transportation cost. In this study, a driver's travel decision-making process is decomposed into two steps: i) making at least one trip or just staying at home in the survey day, which is

[8] Although the Beijing police department claimed that a vehicle could be fined several times in one day, drivers seemed to have different perceptions at that time.

[9] The chance to win a registration was 35 to 1 in July 2011, according to a report by Reuters at http://www.reuters.com/article/2011/07/28/us-china-cars-lottery-idUSTRE76R21R20110728.

estimated using a binary logit model; and ii) the number of trips given making at least one trip, estimated using an OLS model.

For two groups of drivers in households who live within the 5^{th} ring road and have only one vehicle, drivers under restrictions on average have 2.48 trips per day, significantly lower than 2.58 trips made by drivers unaffected in the survey day (t-ratio -1.73, significant at 0.05 level). 11.0% drivers under restrictions choose to stay at home, higher than 9.2% of those unaffected. Excluding drivers who stay at home, the average daily trip frequency of the former (2.79) is lower than that of the latter (2.84), however, insignificantly (t-ratio -1.00). Looking at only auto trips, drivers under restrictions have 1.36 trips per day, significantly lower than 1.67 trips made by drivers unaffected in the survey day (t-ratio -5.27, significantly at 0.01 level). 47.3% of drivers facing restrictions make no auto trips, higher than 38.0% of those unaffected. Similarly, excluding drivers having no auto trips, the average daily auto trip frequency of the former (2.58) is lower than of the latter (2.69), however, only marginally significantly (t-ratio -1.76, significant at 0.10 level). The above figures suggest that driving restrictions have larger effect on the first step in decision-making, that is, whether to go out or stay at home, compared to the number of trips after one has decided to go out.

In this section, we examine first the effect on auto trip frequency of driving restrictions since it is closely related to travel congestion and air pollution, and then the effect on total trip frequency. For both of them, we further differentiate work trips and non-work trips primarily due to the fact that people have more flexibility in adjusting non-work travel than work travel. By adding time dummies and interactive variables mentioned earlier, we look at how individuals make inter-temporal adjustment on their travel behaviors and how the adjustments vary across population groups. Finally we investigate the "4&9" effect, that is, how people adjust their travel behaviors in response to the relatively high traffic flow in the 4&9 restricted day.

5.1. Auto trip frequency

First, we investigate the effect of driving restrictions on the possibility of making at least one auto trip[10]. Equation 1 includes only the restriction dummy, to show the overall effect of driving restrictions. Equation 2 adds time dummies- whether it is the day just before a driver's restricted day, and whether it is the day just after the restricted day, to examine whether there is any inter-temporal adjustment in auto use during this small time window. Individual and location variables

[10] Here we include the carpool trip since its ratio among all auto trips is not large.

are added in Equation 3. In Equation 4, several interactive variables are further added to investigate whether the adjustments vary across drivers of various features.

[Insert Table 4-1 around here]

The estimation results are presented in Table 4-1. The estimates of individual variables in Column 3 show that in general male, young drivers are more likely to have auto trips. The possibility of auto use increases with income, as expected. Having a public transit pass is negatively associated with the possibility of having auto trips. Drivers who live in the south are more likely to have auto trips, possibly due to the insufficient provision of public transit there or just the outcome of self-selection in drivers' residential location choice. Similarly, drivers who live nearby metro stations rely less on auto, although no causality could be inferred here. The above estimates also indicate that not every driver uses his/her car on a daily basis.

Looking at the estimates in Column 1 to 3 for the restriction dummy, which is our main focus, the results show that driving restrictions significantly decrease the possibility of auto use for drivers in their restricted day by about 8.5%-9% (in an "average" weekday), compared to those in their unrestricted day. This again indicates that the effect of driving restrictions might be lower than the government's expectation. The coefficients of two time dummies are all not significant in Equation 2-4. Thus, it is possible that facing driving restrictions, people tend to increase the auto use in all unrestricted days within a week, not just one day before or after the restricted day. However, another explanation that the government would like to see, although not credible, is that people simply decrease the auto use in the restricted day without any inter-temporal adjustment.

The estimates for interactive variables in Column 4 indicate that the effects of driving restrictions vary across individuals. Male drivers are more likely to have auto trips even under restrictions. In addition, high-income drivers and those who live in the south tend to decrease the possibility of auto use more when their car use is restricted, possibly due to the high elasticity of auto use possibility to driving restrictions for them since they initially rely more on auto.

We then estimate a multinomial logit model for only 990 drivers surveyed in their restricted day, with choice set consisting of staying at home (109 drivers), having at least one trip but no auto trips (359), and having at least one auto trip (522). The estimation results, given in Table A-1, are mostly consistent with those in Column 4 of Table 4-1. Compared with the other two options, male, young drivers tend to stick to auto use even facing restrictions. Conditional on going out under restrictions, drivers who live in downtown are most likely to use non-auto modes than auto, with those living in suburb next, and those living in exurb least. This could be explained by that: i) higher density and better bus service in urban center facilitate the use of non-auto modes (or people who prefer the combination of non-auto modes and auto choose to live in urban center); ii) people who live far away from urban center tend to make more trips in unrestricted areas; and iii) the odds of being caught for noncompliance decrease with distance to urban center. Also, using non-auto modes other than auto is significantly associated with living close to metro stations, again, with no causality inferred.

The above results indicate that there is significant difference in willingness to pay for car use across individuals of various features or living in various locations, which is ignored by driving restrictions on basis of plate license numbers. Imposing market-based measures, e.g. congestion toll within the 5^{th} ring road, would in this case incur overall welfare gains, suppose that implement costs are not formidably high.

Then, we examine the effect of driving restrictions on the number of auto trips given making at least one auto trip (see Table 4-2)[11]. The estimates in Column 3 show that old drivers, drivers having at least one kid of age 6-12, and those living away from metro stations tend to have more auto trips, conditional on having at least one auto trip. The significant coefficient of the restriction dummy in Column 1 and its insignificance in Column 2 after controlling for two time dummies suggest that there is kind of inter-temporal adjustment in auto use in a 3-day time window. However, there is no evidence of individual-specific effect of driving restrictions from the estimation results in Column 4, which is not surprising since these drivers, as a sub-sample, have possibly found ways to circumvent restrictions.

[Insert Table 4-2 around here]

We also do similar analysis on the possibility of making at least one work trip or non-work trip by auto, respectively. The estimates, not reported here, show that male drivers are more likely to stick to auto use facing restrictions, whether for the purpose of work or of non-work. Drivers who live in the south tend to decrease the possibility of auto use for work when their car use is restricted. While high-income drivers facing restrictions are less likely to have auto trips for non-work.

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[11] We also try trip frequency excluding back-home trips, and the logarithm of trip frequency as dependent variable, which doesn't change the estimation results.

5.2. Total trip frequency

Similarly, we first investigate the effect of driving restrictions on the possibility of making any trip. The estimation results are presented in Table 5-1. The probability of going out instead of staying at home decreases with age, increases with income, and increases with distance to the nearest metro station. The probability of going out is also higher for drivers who having a public transit pass, and those who live in the south. Also, people are more likely to go out when living closer to urban center, possibly due to the high density in urban center or just self-selection.

[Insert Table 5-1 around here]

From the estimates in Column 1, driving restrictions significantly decrease the possibility of making at least one trip for drivers in their restricted day by 1.7% (in an "average" weekday), less than that for auto trips, with drivers in their unrestricted day as reference group. Although the coefficient of the restriction dummy, still negative, loses its significance in Column 2-4, the coefficients of two time dummies are all significant, providing evidence of inter-temporal adjustments on travel behaviors: as a compensation, the possibility of going out in the day just before a driver's restricted day is higher by 2.9%-3.6%, and that of going out in the day just after one's restricted day is higher by 2.0%-2.4%, compared to other weekdays except the restricted day. The estimates for interactive variables in Column 4 show that facing restrictions, middle-income drivers have higher possibility to stay at home, possibly due to their flexibility in rescheduling travels/activities and their reluctance to use alternative modes such as taxi.

Then we examine the effect of driving restrictions on the number of trips given making at least one trip (see Table 5-2). We look at only variables related to restrictions. Generally driving restrictions decrease the trip frequency, however, insignificantly. This suggests that driving restrictions mainly affect drivers' decision on whether to go out rather than the following decision on trip frequency. In addition, driving restrictions have larger effect on female drivers in trip frequency, indicating that they value the comfort provided by car more.

[Insert Table 5-2 around here]

Similar analysis on work and non-work trips, with estimation results unreported, show that drivers make inter-temporal adjustments mainly on work activities, since non-work trips defined in this study include trips of diversified purposes. Driving restrictions have no gender-specific effect on the possibility of making work trips, but have larger effect on female drivers in terms of non-work trips, which is consistent with our expectations.

6. The "4&9" effect

In this section, we examine whether people make inter-temporal adjustments on their travel behaviors in face of the relatively high traffic flow in the 4&9 restricted day.

We first look at only drivers in households who have only car with the last plate license digit not as "4" or "9", live within the 5th ring road, and could use their car in the survey day. Among 3,581 drivers that conform to such criteria, about 23.6% are surveyed in the 4&9 restricted day. Equation 1 to 3 address the possibility of making any trip, while Equation 4 to 6 the number of trips given making at least one trip. Equation 1 and 4 include only the dummy indicating whether it is a 4&9 restricted day, with the weekday variation controlled for. Equation 2 and 5 include also two time dummies, the day just before or after one's restricted day, to take into account the inter-temporal adjustment in travel behaviors identified in previous section. Equation 3 and 6 further includes individual variables.

[Insert Table 6 around here]

[Insert Table 7 around here]

The estimation results, given in Table 6, provide no evidence of inter-temporal adjustments in trip making, i.e., lower trip frequency (or possibility) in the 4&9 restricted day, for these drivers. Similar analysis is also done for only auto trips, with the main results unchanged. However, we find that for non-drivers, the possibility of going out (or trip frequency conditional on going out) is significantly lower in the 4&9 restricted day by about 1.5% (or 0.06 trips), as seen in Table 7. This could be explained by i) less freedom for drivers given the auto reliance and driving restrictions, since now they could only adjust their auto use in four weekdays, and ii) lower elasticity of auto travel demand to traffic volume, possibly due to the comfort and privacy related to auto use. More importantly, the above results indicate that driving restrictions in Beijing are implemented at the cost of even non-drivers, who are supposed to benefit from such policies without paying anything.

In addition, we also compare the daily trip distribution in different days to see whether people choose to circumvent normal peak hours in the 4&9 restricted days but find no difference. A regression of morning peak hour trip ratio on the "4&9" dummy, for whether all trips, all auto trips, or all trips of people who have no car, confirms that there is no extended peak hour in the 4&9 restricted days[12].

There have been some debates about how to change the current digit pairs to make the restrictions uniform within a week. An informal response from the government is that there would still be imbalance no matter which digit is combined with "4". However, it might be worth finding other ways, considering the unnecessary compliance costs imposed on non-drivers identified here.

7. Conclusion

This article examines the effect of Beijing's driving restrictions on individual travel behavior. Travel behaviors, with the focus on trip frequency, are compared across drivers in the day when their car use is restricted and those in their unrestricted day. Driving restrictions decrease the auto use and some drivers switch to other modes like bus. However, the effect of restrictions seems lower than expectation, from the high share of auto trips for drivers under restrictions.

Driving restrictions mainly affect drivers' decision on whether to go out or use auto rather than the number of trips or auto trips given making at least one trip or auto trip. Evidence from both auto trips and all trips indicates that the adjustment in travel behaviors varies across individuals. For example, female, high-income drivers who live in the south of the Beijing central city tend to decrease auto use more facing restrictions. In addition, the article describes how drivers make inter-temporal adjustments in trip making, especially within a 3-day time window. All these provide evidence of the variation in willingness to pay for auto use across individuals and the variation within a week for an individual, ignored by driving restrictions on basis of plate license number. The analysis on the "4&9" effect further shows that non-drivers, who are supposed to benefit from driving restrictions, purposely decrease their trip frequency in the 4&9 restricted days due to the uneven restrictions. Such compliance costs are totally unnecessary and could be avoided through smarter policy design.

The program in Beijing has been emulated in Hangzhou, Chengdu, and other cities in China. However, this article illustrates the compliance costs associated with driving restrictions. Market-based measures such as fuel tax or congestion toll, which allow people of high willingness to pay

[12] Here morning peak hour is defined as 7am-8am, or 6:30am-8:30am.

to stick to auto use through imposing a price mechanism, would theoretically incur overall welfare gains, suppose that implement costs are not formidably high. Moreover, the limited effect of Beijing's driving restrictions is on basis of restricting people's long-run adaptation by a car registration lottery program, which has greatly changed the local auto market, e.g., the decrease in auto sale and the change in market structure. Such additional policy costs could also be avoided by the introduction of market-based measures.

We are currently working on another paper that investigates the effect of driving restrictions on labor supply by distinguishing fixed-time workers and discretionary-time workers, following Viard and Fu (2011). Other directions include: i) the effect on air quality, if the sample provided by 2010 Survey could well describe the overall traffic in one day or even in certain area; and ii) the effect on firms' or retailers' location choice, e.g., taking high-tech firms in Haidian District as examples.

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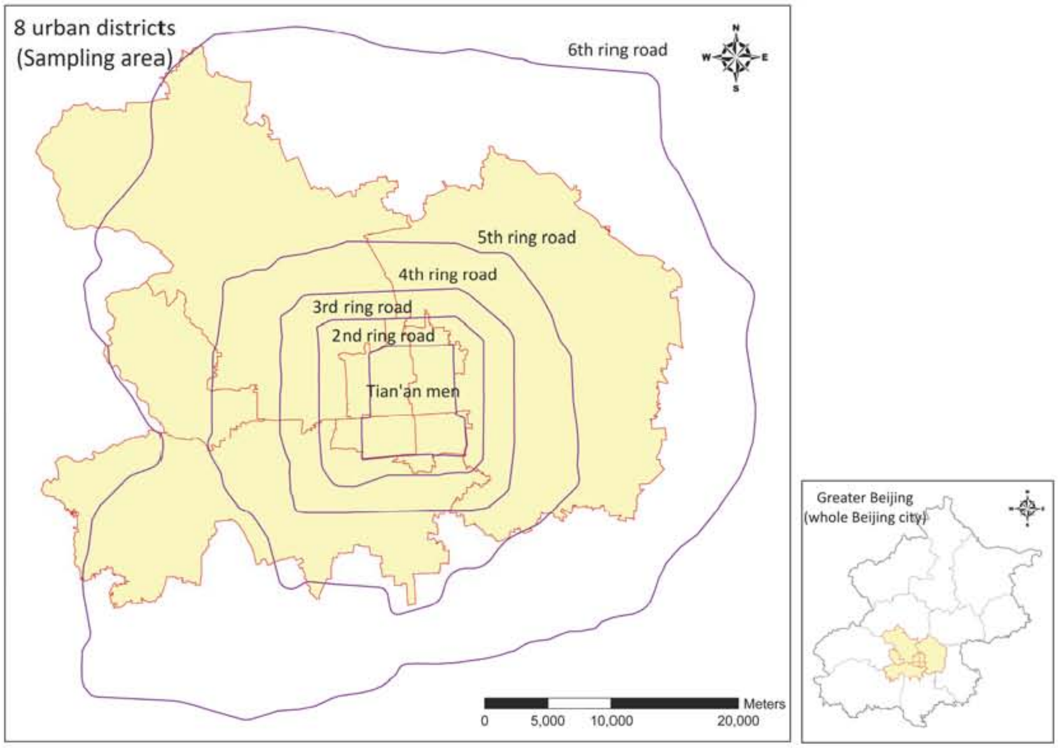

Figure 1. The map of Beijing City and 8 urban districts

Note: Downtown refers to 2 innermost urban districts approximately within the 3rd ring road, Suburb refers to the 4 districts neighboring Downtown, and Exurb refers to the other 10 districts.

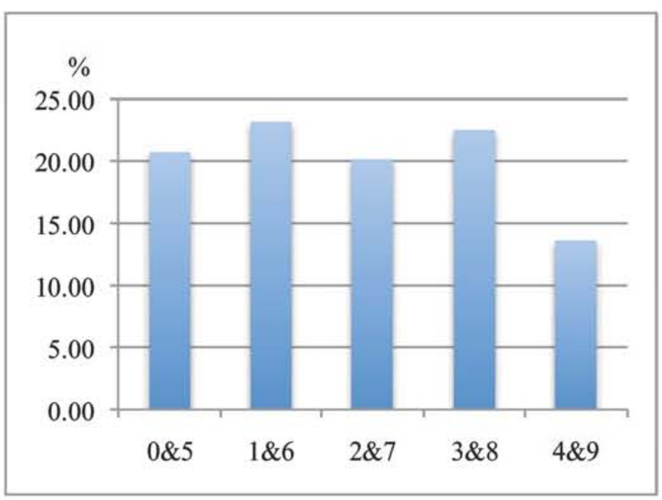

Figure 2. Share of vehicles with different last digits for sampled households

Table 1. Summary statistics

5,123 obs.	Variable	Definition	Mean	SD	Min	Max
Individual	male	1 male, 0 female	0.77	0.42	0	1
	age		40.75	10.63	18	98
	kids	1 having at least a kid of age 6 to 12, 0 no	0.14	0.35	0	1
	inc_low	annual household income lower than 50,000 RMB	0.34	0.47	0	1
	inc_med	annual household income between 50,000 and 100,000 RMB	0.47	0.50	0	1
	inc_high	annual household income greater than 100,000 RMB	0.18	0.39	0	1
	monthpass	1 having any public transit pass, 0 no	0.88	0.33	0	1
Location	downtown	1 residence in two innermost districts (Dongcheng and Xicheng), 0 no	0.31	0.46	0	1
	suburb	1 residence in four districts adjacent to downtown (Chaoyang, Haidian, Fengtai, and Shijingshan), 0 no	0.65	0.48	0	1
	exurb	1 residence in other ten districts far away from urban center, 0 no	0.04	0.20	0	1
	north	1 residence to the north of Chang'an Street, 0 no	0.51	0.50	0	1
	dist_metro	air distance to the nearest metro station from the centroid of the TAZ in which the respondent lives (km)	1.80	1.44	0.27	8.04
Survey day	Mon	1 Mon as survey day, 0 no	0.22	0.41	0	1
	Tue	1 Tue as survey day, 0 no	0.22	0.41	0	1
	Wed	1 Wed as survey day, 0 no	0.22	0.42	0	1
	Thu	1 Thu as survey day, 0 no	0.16	0.36	0	1
	Fri	1 Fri as survey day, 0 no	0.18	0.39	0	1
Restriction	before_res	1 the day just before a driver's restricted day, 0 no	0.18	0.39	0	1
	restrict	1 the day when a driver's car is restricted for use, 0 no	0.19	0.39	0	1
	after_res	1 the day just after a driver's restricted day, 0 no	0.17	0.38	0	1
	res_male	restrict multiplied by male	0.15	0.36	0	1
	res_kids	restrict multiplied by kids	0.03	0.16	0	1
	res_incmed	restrict multiplied by inc_med	0.09	0.28	0	1
	res_inchigh	restrict multiplied by inc_high	0.04	0.19	0	1
	res_dtown	restrict multiplied by downtown	0.06	0.24	0	1
	res_sub	restrict multiplied by suburb	0.13	0.33	0	1
	res_north	restrict multiplied by north	0.10	0.30	0	1
	res_metro	restrict multiplied by dist_metro	346.71	946.24	0.00	8040.02
Trip frequency	trip_num	number of total trips	2.56	1.60	0	12
	bitrip	1 having at least one trip in the survey day, 0 no	0.90	0.29	0	1

	work_num	number of total work trips	0.82	0.60	0	5
	biwork	1 having at least one work trip in the survey day, 0 no	0.72	0.45	0	1
	nonwork_num	number of total non-work trips	0.74	1.04	0	9
	binonwork	1 having at least one non-work trip in the survey day, 0 no	0.47	0.50	0	1
	auto_num	number of total auto trips	1.61	1.65	0	12
	biauto	1 having at least one auto trip in the survey day, 0 no	0.60	0.49	0	1
	auto_work	number of total auto work trips	0.53	0.58	0	5
	biauto_work	1 having at least one auto work trip in the survey day, 0 no	0.49	0.50	0	1
	auto_nonwork	number of total auto non-work trips	0.39	0.88	0	8
	biauto_nonwork	1 having at least one non-work trip in the survey day, 0 no	0.23	0.42	0	1

Table 2. Vehicle restriction rules during the 2010 Survey

Last digit restricted	Mon	Tue	Wed	Thu	Fri
Sept 8 – Oct 9, 2010	0&5	1&6	2&7	3&8	4&9
Oct 10 – Oct 31, 2010	4&9	0&5	1&6	2&7	3&8

Table 3. Modal split of drivers in their restricted day and those in their unrestricted day

Mode	Restricted		Unrestricted		Difference in share (%)
	Frequency	Percent (I)	Frequency	Percent (II)	I-II
walk	382	15.5	1,653	15.5	0.0
car	1,346	54.7	6,887	64.5	-9.8
pickup truck	28	1.1	51	0.5	0.7
truck	13	0.5	7	0.1	0.5
motor	10	0.4	20	0.2	0.2
metro	88	3.6	384	3.6	0.0
bus	270	11.0	718	6.7	4.3
taxi	57	2.3	92	0.9	1.5
firm bus	43	1.8	109	1.0	0.7
school bus	0	0.0	2	0.0	0.0
illegal taxi/motor	0	0.0	8	0.1	-0.1
bicycle	181	7.4	617	5.8	1.6
electric bicycle	41	1.7	116	1.1	0.6
other	0	0.0	7	0.1	-0.1
total	2,459	100.0	10,671	100.0	

Note: the statistics here are calculated for 5,123 drivers with complete information who live within the 5^{th} ring road and have only one vehicle.

Table 4-1. Estimation results of the binary logit model of auto trip frequency
(Dependent variable: biauto, whether having any auto trip)

	(1)	(2)	(3)	(4)
restrict	-0.380	-0.359	-0.362	-0.491
	(0.071)***	(0.077)***	(0.078)***	(0.517)
before_res		0.105	0.103	0.099
		(0.083)	(0.084)	(0.084)
after_res		-0.013	0.003	-0.000
		(0.085)	(0.086)	(0.086)
male			0.173	0.072
			(0.069)**	(0.077)
age			-0.016	-0.016
			(0.003)***	(0.003)***
kids			-0.016	-0.026
			(0.084)	(0.093)
inc_med			0.263	0.311
			(0.065)***	(0.073)***
inc_high			0.448	0.538
			(0.086)***	(0.098)***
monthpass			-0.460	-0.464
			(0.094)***	(0.095)***
downtown			-0.149	-0.078
			(0.185)	(0.206)
suburb			-0.101	-0.023
			(0.172)	(0.191)
north			-0.152	-0.219
			(0.063)**	(0.071)***
dist_metro			0.079	0.066
			(0.026)***	(0.029)**
res_male				0.519
				(0.177)***
res_kids				0.039
				(0.212)
res_incmed				-0.228
				(0.164)
res_inchigh				-0.403
				(0.207)*
res_dtown				-0.385
				(0.468)
res_sub				-0.416
				(0.439)
res_north				0.321
				(0.157)**
res_metro				0.071
				(0.064)
weekday dummies	Not reported			
constant	0.477	0.449	1.241	1.264
	(0.062)***	(0.067)***	(0.257)***	(0.276)***
N	5,123	5,123	5,123	5,123
log likelihood	-3426.4	-3425.4	-3357.2	-3347.8

Note: 1) standard errors are in parenthesis. 2) * $p<0.10$; ** $p<0.05$; *** $p<0.01$

Table 4-2. Estimation results of the OLS model of auto trip frequency
(Dependent variable: auto_num, number of total auto trips; for only auto_num>0)

	(1)	(2)	(3)	(4)
restrict	-0.110	-0.082	-0.085	-0.345
	(0.062)*	(0.067)	(0.066)	(0.402)
before_res		0.057	0.055	0.055
		(0.065)	(0.064)	(0.065)
after_res		0.071	0.082	0.083
		(0.068)	(0.068)	(0.068)
male			0.037	0.034
			(0.057)	(0.061)
age			0.004	0.004
			(0.002)*	(0.002)*
kids			0.406	0.447
			(0.067)***	(0.073)***
inc_med			-0.028	-0.041
			(0.053)	(0.059)
inc_high			0.225	0.218
			(0.067)***	(0.074)***
monthpass			0.035	0.037
			(0.067)	(0.067)
downtown			-0.116	-0.145
			(0.134)	(0.150)
suburb			0.038	0.015
			(0.122)	(0.136)
north			-0.046	-0.064
			(0.050)	(0.055)
dist_metro			0.041	0.040
			(0.019)**	(0.022)*
res_male				0.025
				(0.162)
res_kids				-0.253
				(0.182)
res_incmed				0.068
				(0.142)
res_inchigh				0.032
				(0.174)
res_dtown				0.189
				(0.344)
res_sub				0.150
				(0.313)
res_north				0.111
				(0.135)
res_metro				0.015
				(0.051)
Weekday dummies	Not reported			
constant	2.625	2.607	2.249	2.283
	(0.051)***	(0.054)***	(0.194)***	(0.207)***
N	3,084	3,084	3,084	3,084
R^2	0.00	0.00	0.03	0.03

Note: 1) standard errors are in parenthesis. 2) * p<0.10; ** p<0.05; *** p<0.01

Table 5-1. Estimation results of the binary logit model of all trip frequency (Dependent variable: bitrip, whether having any trip)

	(1)	(2)	(3)	(4)
restrict	-0.200	-0.068	-0.080	-0.778
	(0.115)*	(0.123)	(0.124)	(0.710)
before_res		0.387	0.369	0.366
		(0.147)***	(0.148)**	(0.148)**
after_res		0.254	0.271	0.268
		(0.146)*	(0.147)*	(0.147)*
male			-0.105	-0.210
			(0.120)	(0.139)
age			-0.020	-0.020
			(0.004)***	(0.004)***
kids			0.229	0.222
			(0.150)	(0.169)
inc_med			0.241	0.361
			(0.104)**	(0.117)***
inc_high			0.553	0.650
			(0.152)***	(0.174)***
monthpass			0.478	0.475
			(0.130)***	(0.131)***
downtown			0.756	0.638
			(0.272)***	(0.316)**
suburb			0.577	0.424
			(0.247)**	(0.286)
north			-0.284	-0.294
			(0.106)***	(0.120)**
dist_metro			0.072	0.063
			(0.042)*	(0.048)
res_male				0.447
				(0.279)
res_kids				0.011
				(0.366)
res_incmed				-0.541
				(0.257)**
res_inchigh				-0.444
				(0.356)
res_dtown				0.513
				(0.628)
res_sub				0.640
				(0.572)
res_north				0.036
				(0.254)
res_metro				0.041
				(0.102)
weekday dummies	Not reported			
constant	2.222	2.117	1.821	2.001
	(0.102)***	(0.107)***	(0.387)***	(0.427)***
N	5,123	5,123	5,123	5,123
log likelihood	-1614.4	-1610.1	-1573.5	-1569.0

Note: 1) standard errors are in parenthesis. 2) * $p<0.10$; ** $p<0.05$; *** $p<0.01$

Table 5-2. Estimation results of the OLS model of all trip frequency
(Dependent variable: trip_num, number of total trips; for only trip_num>0)

	(1)	(2)	(3)	(4)
restrict	-0.057	-0.027	-0.030	-0.502
	(0.054)	(0.058)	(0.058)	(0.377)
before_res		0.048	0.048	0.047
		(0.060)	(0.059)	(0.059)
after_res		0.085	0.083	0.084
		(0.062)	(0.061)	(0.061)
male			-0.055	-0.108
			(0.050)	(0.055)**
age			0.008	0.008
			(0.002)***	(0.002)***
kids			0.457	0.456
			(0.060)***	(0.066)***
inc_med			-0.012	-0.022
			(0.047)	(0.053)
inc_high			0.161	0.159
			(0.061)***	(0.068)**
monthpass			0.063	0.063
			(0.066)	(0.066)
downtown			-0.007	-0.039
			(0.130)	(0.144)
suburb			0.067	0.057
			(0.120)	(0.132)
north			-0.075	-0.098
			(0.045)*	(0.050)*
dist_metro			0.033	0.030
			(0.018)*	(0.020)
res_male				0.302
				(0.130)**
res_kids				-0.002
				(0.154)
res_incmed				0.063
				(0.121)
res_inchigh				0.019
				(0.149)
res_dtown				0.194
				(0.335)
res_sub				0.090
				(0.311)
res_north				0.111
				(0.115)
res_metro				0.016
				(0.046)
Weekday dummies	Not reported			
constant	2.794	2.777	2.301	2.378
	(0.046)***	(0.049)***	(0.181)***	(0.194)***
N	3,084	3,084	3,084	3,084
R^2	0.00	0.00	0.02	0.02

Note: 1) standard errors are in parenthesis. 2) * p<0.10; ** p<0.05; *** p<0.01

Table 6. Estimation results of the "4&9" model for drivers

	Binary logit model Dependent variable: bitrip			OLS model Dependent variable: trip_num, for trip_num>0		
	(1)	(2)	(3)	(4)	(5)	(6)
day49	-0.066	-0.039	-0.055	0.029	0.034	0.039
	(0.170)	(0.170)	(0.172)	(0.078)	(0.078)	(0.077)
before_res		0.389	0.367		0.053	0.057
		(0.157)**	(0.158)**		(0.063)	(0.063)
after_res		0.300	0.320		0.078	0.076
		(0.164)*	(0.166)*		(0.067)	(0.067)
male			-0.249			-0.059
			(0.154)			(0.059)
age			-0.020			0.009
			(0.005)***			(0.002)***
kids			0.192			0.442
			(0.184)			(0.071)***
inc_med			0.423			-0.050
			(0.129)***			(0.056)
inc_high			0.545			0.110
			(0.183)***			(0.073)
monthpass			0.424			0.132
			(0.159)***			(0.077)*
downtown			0.785			-0.100
			(0.335)**			(0.154)
suburb			0.539			0.038
			(0.301)*			(0.142)
north			-0.303			-0.100
			(0.131)**			(0.054)*
dist_metro			0.053			0.024
			(0.051)			(0.021)
weekday dummies	Not reported					
_cons	2.215	2.093	1.965	2.742	2.723	2.251
	(0.142)***	(0.149)***	(0.479)***	(0.064)***	(0.068)***	(0.216)***
N	3,581	3,581	3,581	3,260	3,260	3,260
log likelihood	-1075.1	-1071.2	-1042.8			
R^2				0.00	0.00	0.02

Note: 1) standard errors are in parenthesis. 2) * p<0.10; ** p<0.05; *** p<0.01

Table 7. Estimation results of the "4&9" model for people who have no car

	Binary logit model Dependent variable: bitrip		OLS model Dependent variable: trip_num, for trip_num>0	
	(1)	(2)	(3)	(4)
day49	-0.096	-0.094	-0.060	-0.060
	(0.042)**	(0.045)**	(0.025)**	(0.025)**
male		0.202		-0.081
		(0.029)***		(0.016)***
age		-0.037		0.013
		(0.001)***		(0.000)***
kids		0.271		0.302
		(0.060)***		(0.026)***
inc_med		0.106		-0.001
		(0.033)***		(0.017)
inc_high		0.265		0.021
		(0.077)***		(0.035)
monthpass		0.876		-0.072
		(0.059)***		(0.039)*
downtown		0.575		0.115
		(0.115)***		(0.064)*
suburb		0.251		0.093
		(0.110)**		(0.061)
north		-0.198		-0.013
		(0.031)***		(0.017)
dist_metro		0.054		0.021
		(0.014)***		(0.007)***
weekday dummies	Not reported			
_cons	1.364	1.948	2.695	2.062
	(0.035)***	(0.142)***	(0.020)***	(0.081)***
N	32,170	32,170	25,278	25,278
log likelihood	-16701.1	-15214.1		
R^2			0.00	0.04

Note: 1) standard errors are in parenthesis. 2) * p<0.10; ** p<0.05; *** p<0.01

Appendix

Table A-1: Estimation Results of the MNL model of auto use for drivers under restrictions

Base: having at least one auto trip	Staying at home	Having at least one trip but no auto trips
male	-0.546	-0.641
	(0.261)**	(0.172)***
age	0.032	0.022
	(0.010)***	(0.007)***
kids	-0.158	0.063
	(0.339)	(0.203)
inc_med	0.112	-0.150
	(0.239)	(0.161)
inc_high	-0.212	-0.076
	(0.323)	(0.196)
monthpass	-0.310	0.516
	(0.303)	(0.245)**
downtown	-0.853	1.244
	(0.560)	(0.587)**
suburb	-0.800	1.191
	(0.509)	(0.566)**
north	0.158	-0.183
	(0.235)	(0.152)
dist_metro	-0.144	-0.131
	(0.094)	(0.063)**
weekday dummies	Not reported	
constant	-1.539	-2.093
	(0.837)	(0.737)**
N	990	
Log likelihood	-903.4	

Note: 1) standard errors are in parenthesis. 2) * $p<0.10$; ** $p<0.05$; *** $p<0.01$