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Home parking convenience, household car usage, and implications to residential parking policies

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ABSTRACT

This paper investigates the effect of home parking convenience on households' car usage, and the implications to residential parking policies. A random sample of 840 households is selected from a travel survey in the New York City region, and their home parking types are identified through Google Street View. It found that with the same car ownership level, households without off-street parking used cars much less, and relied more on alternative modes than those with off-street parking. For households with access to both garage and street parking, those who use the handy street parking tend to make more car tours than those who do not. In general, convenient home parking encourages households' car usage. Policy implications to the minimum off-street parking requirement, residents parking permit, street cleaning, and new urbanism neighborhood design are discussed.

1. Introduction

A large portion of parking studies focused on various travel outcomes ranging from mode choice (Wilson and Shoup, 1990; Shoup, 1997; Hess, 2001; Shiftan and Golani, 2005; Su and Zhou, 2012), transit ridership (Mildner et al., 1998), trip generation (Comsis Corporation, 1994, Dueker et al., 1998; Kelly and Clinch, 2009), trip length (parking cruise) (Shoup, 2005; Arnott and Rowse, 2009), vehicle miles traveled (VMT) (Deakin et al., 1996, Vaca and Richard Kuzmyak, 2005), trip start time (Shiftan and Burd-Eden, 2001; Nurul Habib et al., 2012), and the overall car usage (Topp, 1993; McCahill and Garrick, 2010), to parking location (Gillen, 1978; Feeney, 1989; Hensher and King, 2001) and trip destination (Shiftan et al., 2004; Marsden, 2006). Most of them have focused on parking at the destination end (e.g., urban centers or shopping malls) instead of the home origin of trips.

Meanwhile, the few studies on the home-origin parking have traditionally focused on effects on the housing market, such as housing affordability (Jia and Wachs, 1999; Klipp, 2004; Litman, 2010; McDonnell et al., 2011), instead of the transportation market, such as car ownership and usage. The preference to the destination-end parking is understandable because this type of parking is directly attached to specific trips or traffic (outcome is easy to measure), sometimes displays the price signal in market (theoretical explanation is straightforward), is often less controversial, and policies are relatively easier to enforce. However, the overlooking of the home-origin parking is certainly unsatisfactory because it makes up the majority of the entire parking stock, e.g., 75 percent of all parking spaces in London (TfL (Transport for London), 1999), and could have a more profound effect on the travel outcome than the destination-end parking (thinking of car ownership).

Our prior study confirmed the effect of the home-origin parking on households' car ownership decision after controlling for the supply–demand endogeneity (Guo, 2013). This paper aims to examine the effect on household car usage given the same car ownership level—basically whether different types of home parking 'make' some households use cars more than others even though they have the same number of cars. Because most households do not pay for home parking at a per usage base, a new concept of "parking convenience" is developed to explain the home parking effect on travel decisions. The New York City case study demonstrates the significant influence of parking convenience on households' trip mode choice, trip frequency, and VMT. In general, convenient parking leads to more car usage.

The findings help assess residential parking policies from a new perspective. These policies include but are not limited to the minimum off-street parking regulation that mandates off-street parking, the minimum street width requirement that mandates on-street parking, and design guidelines that regulate many attributes of an on-site garage, such as its location, driveway width, door width, etc. Given that residential parking policies have suffered from a dearth of research evidence (Marsden, 2006),

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the research makes a positive contribution to the parking literature and the current parking policy debate.

2. Parking convenience: framework

Parking convenience is defined to cover two attributes of parking at the home origin: (1) the convenience to find a parking space at a desired place and a desired time (parking certainty), and (2) the convenience to move the car in and out of the parking place (parking ease). Both attributes vary by parking types and the neighborhood built environment.

2.1. Definition of parking convenience

Regarding parking certainty, when a household has their own garage or driveway, the parking space, location, and time are often guaranteed with certainty. The opposite example is on-street parking, where neither the space, location, nor time is guaranteed. In this case, the convenience of parking depends on the level of competition for street parking. In an urban neighborhood with a high density but a limited supply of street parking, it might be difficult to find a space at all on the street, while in a low-density suburban setting, street parking is abundant and almost guaranteed at any time. The intermediate case might be shared garage, driveway, or parking lot in multifamily developments, where a household may have a guaranteed but unreserved parking spot.

Regarding parking ease, off-street parking like garage or parking lot needs accessory space to connect with streets, while street parking does not. The former may take a longer time to park than the latter. However, street parking (most likely parallel parking) could be more challenging than vertical parking (most off-street parking), but the difficulty level also depends on the street width and parking crowding level. The types of garage also matter. A large underground garage in a residential complex is certainly more difficult to navigate than a garage in a single family home. Even within the latter, the location (facing street or at the backyard connected by a driveway) and the door width of the garage are important factors too. They will affect the ease of maneuvering a car in and out of the parking space and the parking flexibility, or the possibility of one parked car blocking other parking spaces.

Does home parking convenience affect households' car usage? Conceptually, it should. Parking is part of a car trip, and the cost and convenience of parking, be it at the trip destination or home origin, should affect the (dis)utility of car travel. If parking becomes inconvenient, the disutility of the car trip should increase, and a household will make fewer car trips. The effect of parking certainty is relatively straightforward. To illustrate the parking ease effect on car usage, assuming that there are two identical households, A and B, who live in the two single-family homes side-by-side in Fig. 1 (left). Both own one car and a garage in the backyard connected to the street by the shared narrow drive alley. Supposing that household A *happened* to park the car on the street while household B *happened* to park inside the garage yesterday. Now, today, both A and B want to go to a supermarket located 10 min away by foot. Because pulling the car out of the garage is so inconvenient, B may end up walking to the supermarket or consolidating it with another one, while A may simply jump in the car already parked on the street and drive there.

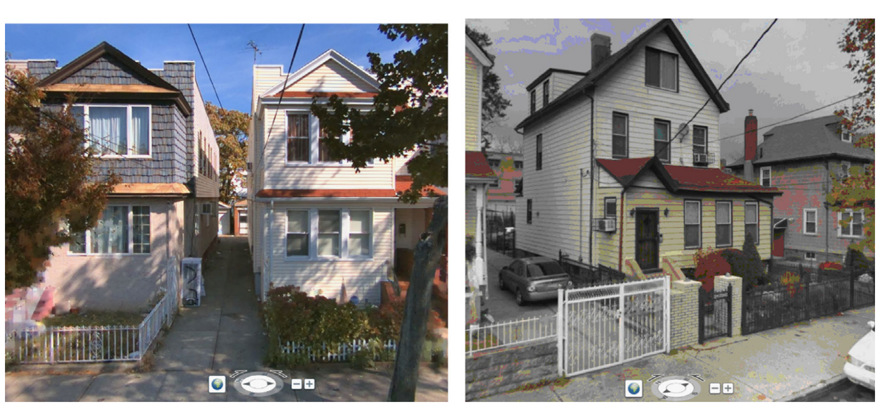
Therefore, inconvenient parking at home may lead to several possible outcomes: households may (1) make the same number of trips but switch to other non-car modes; (2) reduce the number of trips by forgoing some of the car trips; and (3) combine several car trips into one trip. This means that parking convenience may affect mode choice, trip frequency, VMT, and trip chaining. Whether this convenience effect is large enough to be measured is an empirical question.

Only several studies have examined this parking convenience–car usage relationship, and all found a positive connection. For example, Balcombe and York (1993) surveyed eight sites in south England in the early 1990s and found that the convenience of finding an (on-street) parking space may affect the car type and car usage. Residents were reluctant to use their cars if they may lose the parking space. Pendola et al. (2005) compared the mode share and car trips between a small sample households ($N=42$) with and without off-street parking in a handful of developments, and found that the former owned more cars and used them more frequently than the latter. Sherman (2010) did a similar study but for a larger sample ($N=182$) and found those with off-street parking tended to make more car trips and more likely commute to work by car. Weinberger et al. (2012) found a similar pattern on commuting mode between neighborhoods with different shares of households with off-street parking. All these studies focused on parking certainty, and the authors have not identified a single study on parking ease.

2.2. Measurement of parking convenience

The dependent variables are travel outcomes such as mode choice, car usage frequency, and VMT. The independent variables include parking convenience, variables of interest, and control variables such as social–economic attributes, built environments, and transportation supply. The measurement of parking convenience merits discussion.

First, parking certainty is difficult to measure and collect through self-reported surveys. Such certainty depends on the



Narrow Drive Alley   Fence Gate

Fig. 1. Typical types of off-street parking in the study region. *Source*: Bing Map.

parking supply and demand in a neighborhood, inside a building, or within the same household. For on-street parking, certainty is reflected by the combination of search time and acceptable distance between the parking location and home, which may vary by time of day and days in a week. For off-street parking, it may depend on the agreement between the landlord and tenants, or among tenants themselves and household members. Parking certainty and parking types are closely correlated, but do not exactly overlap. A simplified but still reasonable measure is using parking types as proxies of parking certainty, as did most prior studies. In this case, parking certainty is measured as the available parking type that ensures the highest certainty to a household (see below).

Parking ease can be measured by many street and building design features: for example, street width and crowding level for street parking, and garage door width, drive alley width, location of garage, automatic garage door, etc. for garage parking. However, these features only take effect when a household park in the associated parking places (street, driveway, or garage). Therefore, instead of including them as independent variables to measure parking ease, the parking location (on street, in driveway, or in garage) is used as a proxy of parking ease, assuming each location is attached with a unique set of easement features.

Second is the unit of analysis. The dependent variables are measured either at the trip level (mode choice) or at the household level (trip frequency and VMT), while parking convenience is measured at the parking type level, e.g., street parking, garage, or driveway. Linking parking certainty to either trip or household levels of decision is straightforward. For example, parking certainty matters only when driving back home, so the parking type at the end of the trip should be measured. However, when a household make the trip decision, they consider the parking certainty from all available parking options back home, not just the one they eventually used. Therefore, within multiple parking options available to a household, the one with the highest certainty is used as the certainty measure for all home-based trips for that household.

Linking parking ease to trip-level decisions is more complex. Different from parking certainty, parking ease affects the decision-making on the next trip (whether a driver bothers to move the car out of the parking place or not), so the parking type at the beginning of the trip should be measured. In reality, no travel surveys record parking type before travel. This would not a problem if the particular car can be tracked, so its parking type after the 1^{st} trip will become the parking type before the 2nd trip. However, no travel surveys link a specific vehicle to a specific trip, so cars can only be tracked for the one-car households. For households with multiple cars, there is no way to link the parking location of a car to its subsequent usage. One compromise is not to link the parking ease to a specific trip but to all trips made by the household on the survey day. In this case, it becomes an event measure—whether the household ever use that particular parking location or not, and the dependent variable would become the *extra* home-based trips. This compromise would not be a problem if households make a few home-based car trips, in which case the parking ease effect will be largely captured by subsequent trips. In the New York City example, the average number of home-based car trips per household is 1.8 (Table 5).

The measurement of parking convenience indicates that the parking certainty can be modeled for both mode choice (trip level) and trip frequency (household level), while parking ease can only be modeled for the latter.

2.3. Estimation of parking convenience: selection bias and endogeneity

In model estimation, the convenience effect is affected by both selection bias and endogeneity. They perform differently for parking certainty and parking ease. Since the parking effect on car usage (given car ownership) matters only when households own cars, including non-car households will introduce the selection bias of car ownership (Dubin and McFaddden, 1984). This type of selection bias applies to both parking certainty and parking ease. The latter has another type of selection bias of parking type. If parking ease is measured as whether a household parked on the street or not, all households should have the same set of parking options because the probability of parking on the street differs between households with and without off-street parking. Note that parking ease has another constraint: only those households who used cars revealed their parking locations have the parking ease measure. Therefore, the parking certainty model is for all car-owning households, while the parking ease model is for households who own and used cars on the survey day, and have the same parking options (e.g., all have garage, driveway, and street parking available). This suggests that parking ease can only be estimated for households with the same level of parking certainty. Such a research design avoids the selection bias.

Endogeneity may occur for both parking certainty and parking ease. For parking certainty, endogeneity exists if parking types affect car ownership. Because car ownership is a strong determinant of car usage, the parking certainty (type) effect will be biased without controlling for car ownership. Including car ownership mitigates the problem, but may not preclude the endogeneity if unobservable factors (e.g., attitudes and preferences) involve in the parking type and car ownership relationship. One solution is to use instrumental variables associated with car ownership but not with parking types. Another solution is to target households with the same car ownership level. This paper uses the latter because, as shown in the case study, for households who own cars, their car ownership is very similar regardless of their parking types

Table 1
Household travel pattern by parking types.

Parking type	All households ($N=840$)								
	Own car	Households with cars ($N=554$)							
		# car per HH	Avg. # H-B car tours[a]	Car mode share[b]	Tot km [c]	Households used cars ($N=373$)			
						Car Used	Avg. # H-B car tours[a]	Tot km [c]	# of stops
Garage ($N=266$)	217 (82%)	1.65	1.38	0.67	38.7	167 (77%)	1.75	47.5	2.78
Driveway ($N=178$)	144 (81%)	1.44	1.42	0.67	37.4	102 (71%)	1.92	48.1	2.88
On-street ($N=396$)	193 (49%)	1.40	0.85	0.48	26.2	104 (54%)	1.55	41.1	2.80

[a] H-B Car tour: a complete home-based car tour starting from and ending at home, driver only.
[b] All trips by car (drivers+passengers), transit, walking, etc. starting from home, the first leg of the home-based tour.
[c] Average weekday VMT by household, counting only drivers and not passengers.

(Table 1) and their parking locations on the survey day (Table 5). The endogeneity of car ownership is addressed through research design and not statistical models.

Parking ease has another type of potential endogeneity: a household may decide to make another trip first, and then park on a preferred location (e.g., on the street instead of inside a garage) convenient for the subsequent trip-making. In this case, the estimation of parking ease (associated with street parking) on trip frequency will be biased. To preclude this potential endogeneity, households have to decide where to park at home after completing trip_n, irrelevant to the "yes or no" decision on trip_{n+1}. One solution to the problem is to find instrumental variables that affect the probability of parking on streets but are still unrelated to trip making. Possible instruments for parking on streets include but are not limited to whether a household uses garage for storage and not car parking, vehicle type (RAC Foundation, 2005), presence of vandalism, housing design, lot size, street width, overnight parking regulations, garage technology, driver characteristics, etc. The exact set of choices varies from region to region.

This paper selects six instrumental variables suitable for the case study area: location of the garage, the presence of narrow drive alley to the garage or a fence gate at the entrance, the presence of driveway or parking yard abutting street, ownership of the property, and housing types[1] . The first two factors certainly affect the chance of parking on streets. The third factor refers to whether a household can park on site in the front of their residence, which occurs normally when the driveway is not shared with a neighboring building, or not separated by a fence and gate from the street. Ownership might matter because homeowners may not share parking with other tenants, and have the flexibility of modifying their property for parking convenience, legally or illegally, as observed in many neighborhoods in the study region (Mooney, 2008; New York City Department of City Planning (NYCDCP), 2009). Housing types (e.g., apartments, single family detached, or attached) affect all the above factors. The six variables affect the chance to park on streets but should not directly correlate with trip making given a car ownership level.

The control function approach (Rivers and Vuong, 1988; Berry et al., 1995; Blundell and Powell, 2004) is adopted to correct the endogeneity. While the traditional instrumental variable approach replaces the endogenous independent variable with its predicted values estimated from a first-stage model using instrumental variables, the control function adds the residual of the endogenous variable from the first-stage model as a new variable to the main model while retaining the original endogenous variable. The choice between the two approaches is mainly a trade-off between efficiency and robustness against non-normality (Vella and Verbeek, 1999), but the control function has some advantages since it depends less on the quality of instruments (Bollen et al., 1995), provides information about the sorting process (Vella and Verbeek, 1999), and produces estimates often more desirable than the instrumental variable approach (Greene, 2012). Both approaches were tested and produced similar results, but only the control function approach is presented.

3. Case study: New York City region

The study region includes Brooklyn, Queens, Bronx, north Manhattan (110th St north), and 10 municipalities along the Hudson River in New Jersey, which lie outside the urban core (south Manhattan) but are still well served by transit and have a high population density. The main reason to choose this area is its diverse parking supply and a large variation in parking convenience. South Manhattan is excluded partly due to the limits of the data collection method and partly due to the area's homogeneity in parking supply.

The median year of residential buildings in the region is 1947, so many do not have an on-site garage and street parking is the only option. Conversion of front- or back-yards to parking is not rare. Most garages are detached from housing located at the back, not facing streets. They are connected by often narrow driveways difficult to maneuver through (Fig. 1). Street parking is often crowded and competition among neighbors and non-residents is intense. The result is a great mix of various parking types and convenience levels, even often visible within the same street segment.

3.1. Data

A key challenge for this study is to connect a household's detailed travel decisions with their detailed home parking types. The form is normally collected by household travel surveys, which do not record parking supply. Parking is normally not recorded by local governments. The few efforts to inventory residential parking (SFPark, 2010, McDonnell et al., 2011) focus on the buildings and not residents, so are unable to collect household travel behavior information. This study solves the problem by first acquiring a household travel survey with the home address of each household[2] and then measuring their parking conditions through online street level images such as Google Streets Views and Bing Streetside.

Street images have been tested as a reliable information source to auditing pedestrian environments (Clarke et al., 2010), capturing the recovery and abandonment of New Orleans neighborhoods after Katrina (Curtis et al., 2010), counting sprawling parking lots (Davis et al., 2010), and identifying household off-street parking in New York City (Weinberger, 2012). However, this approach does not work well for large buildings where the parking supply is often not visible from the street, so only single family and small apartment buildings (less than 20 units) are analyzed in this research.[3] For most of them, Google Street View reveals the type, size, and location of a garage and driveway, the existence of a fence, and the width of a drive alley.

The travel survey is the most recent one conducted by the New York Metropolitan Transportation Council (NYMTC) in 1998. A random 840 out of a total 1925 surveyed households in the study region are selected. Due to the time gap between the travel survey year (1998) and the parking survey year (2010), some housing units might have been demolished or completely renovated during this period of time. In most situations, a visual check is sufficient to judge whether a building was built after 1998. Local building permit databases and the Certificate of Occupancy database in New York City were also examined, and buildings in either database between 1998 and 2011 are excluded.[4] Therefore, what

[1] Several other instrumental variables are tested including the frequency of street cleaning, the presence of "No Parking at Any Time" signs, and the width of the street, but they have very small t values in both the first and second stage models, and thus are not included.

[2] Household travel surveys do not release home addresses to the public for privacy reasons. The author obtained such information on the 1998 travel survey from the New York Metropolitan Transportation Council (NYMTC) after signing a confidentiality agreement. However, the exception is only valid for the 1998 survey, not for the new 2011 household travel survey that will be released in 2013.

[3] 20 units is the author's choice to make sure that the building is small enough to detect its parking supply on site. The sample has 20 such buildings and their on-site parking spaces are easy to identify from street images, for example, the presence of a parking lot or a visible access to an inside garage. No ramp is detected for underground garages.

[4] What matters here is whether the building changed its parking status by adding or losing off-street parking after 1998. Such a change normally occurs when

is examined here is the parking–travel relationship in 1998 and not 2010, so any household changes (car ownership, family size, income, etc.) after 1998 are irrelevant to the analysis. However, the parking–travel relationship has likely remained stable over the past 13 years because both parking supply and travel pattern evolve very slowly at this regional level.

Because street images form Google and Bing occasionally found different buildings, the Primary Land Use Tax lot Output (PLUTO) map file from New York City was exported to Google Earth so street addresses are linked to specific properties. For households in New Jersey, the description of the building from the NYMTC travel survey (single family attached/detached, apartment size, etc.) is compared with the street images. When inconsistency arises between Google and Bing, a third source, MapQuest, is checked. Normally MapQuest and Bing produced the same result.

4. Parking certainty and car usage

The section analyzes the effect of parking certainty on car usage. It first summarizes the travel patterns by households with different parking certainties (parking types), and then estimates the mode choice and trip frequency using multivariate statistics.

4.1. Travel pattern by parking certainty (type)

Among the 840 households, 47 percent have access only to on-street parking (thereafter on-street households). Thirty-two percent have an on-site garage (thereafter garage households), and 21 percent have driveway but no garage (thereafter driveway households) (Table 1). Eighty percent of off-street households (e.g., have access to garage or driveway) own cars, but that percent for on-street households is only 49, which is expected. However, for households who own cars, the car ownership level is actually quite similar regardless of the available parking types. On average, car-owning on-street households have 1.40 cars, almost identical to the 1.44 cars by the car-owning driveway households ($t=0.4$), and only slightly lower than that (1.65) of car-owning garage households ($t=2.3$). The distributions of car ownership for car-owning households are a little different: 75 percent on-street car-owning households have one car, while the percentages for driveway and garage households are 65 percent and 51 percent.

Among the 554 households with cars, travel patterns differ significantly by parking types. On-street households tend to use their cars less frequently, drive fewer vehicle miles, and are more likely to rely on other travel modes. On average, they made 0.85 home-based car tours on a typical weekday, almost 40 percent less than off-street households ($t=4.4$), drive on average 26.2 km on a weekday, about 30 percent less than off-street households ($t=2.1$), and use cars only for 48 percent of their home-based tours, 28 percent less than off-street households (67 percent, $t=5.9$). A car tour refers to a sequence of car trips starting and ending at the same home address.

To analyze the driving pattern difference, only households who used their cars on the survey day are analyzed (373 households). Seventy-seven percent of garage households used their cars, followed by driveway households with 71 percent. Only 54 percent on-street households used their cars on a typical weekday. They made an average 1.55 tours, 15 percent fewer than the 1.82 average by off-street households ($t=2.6$). However, the average household VMT is slightly less (41.1 vs. 47.8 km) and the difference is insignificant ($t=1.1$).

On trip chaining, all households made almost equal number of intermediate stops in a tour. This is unexpected because on-street households should be motivated to combine trips together in order to reduce the risk of losing the parking space back home. However, the counter argument might be that they are also more likely to use other modes for short-distance trips, which could reduce the number of car trips combined into a tour. The two effects might off-set each other and produce a similar trip-chaining pattern between on-street and off-street households.

This descriptive result is informative but not conclusive because on-street households, as the data shows, tend to live in denser and older neighborhoods closer to jobs and activities centers, and have more convenient transit access and lower income. These attributes have to be controlled in multivariate analyses in order to capture the true effect of parking certainty (type) on car usage. Because the land use attributes and detailed parking attributes are not generated for all households, the sample size for multivariate analyses is smaller: 513 instead of 554 households with cars.

4.2. Modeling mode choice

The mode choice model takes the form of binary logit (Ben-Akiva and Lerman, 1985) with the base being all modes other than cars, including primarily transit and walking. Probit models are also tested and produced consistent results. The control variables include the typical household attributes (income, car ownership, and number of workers) and land use patterns (population and job density around the residence, distance to train station, and land use mix). Because no travel time and cost information for alternative modes is available from the survey, the origin and destination variables and the trip distance are included as proxies. Other attributes like number of kids, household size, neighborhood median year of building, etc. are also tested but insignificant in all models and thus not included.

The mode choice model is first estimated for all households with cars. Since garage households have a little higher car ownership and on-street and driveway households have almost identical car ownership, a separate model is estimated for only on-street and driveway households in order to control the endogeneity of car ownership (besides including the car ownership variable in the model). A third model for all households with just one car was also estimated for the same purpose, but produced consistent results. Given the space limit, only the first two models are presented. The two models are estimated for all trips and then commuting trips (Table 2). The unit of analysis is the first trip leg in a home-based car tour.[5] The 513 car-owning households made 1446 such trips, 415 being commuting trips. The on-street and driveway households made 865 trips with 254 being commuting.

The variable of interest, whether a household has access only to on-street parking, is statistically significant in three models with a negative sign. These households are less likely to use their cars compared to those with off-street parking, even after controlling

(*footnote continued*)
the original building is demolished or a new building is constructed. Minor modifications typically do not change the parking status between off-street and on-street parking. Adding a curb cut to an existing old building is extremely difficult due to strong opposition from the neighborhood because everybody else will lose one precious street parking spot. The New York Times reported several such stories in 2011. Therefore, it is reasonable to assume that if we do not see a new building or a building is not found in the Certificate of Occupancy database, a building's parking status between 1998 and 2011 remains the same. Note that the average building age in New York City is 1941, and buildings built after 1998 only count for a very small portion of the housing stock in the study region.

[5] In the NYMTC survey, mode is specified to a trip not to a tour. A trip may have several segments, each in different modes, such as walk access, subway, and walk egress in a transit trip. In such a situation, a main mode category is defined for this trip, which is transit. In the mode choice analysis, mode is defined as the main mode of the first trip, which is directly affected by parking convenience at home.

Table 2
Parking certainty and mode choice (unit of analysis=home-based trip; base=non-car mode).

Specification=binary logit	Households with cars				Households with cars, no garage			
Independent variable	All trips		Commuting trips		All trips		Commuting trips	
	Beta	*t*	Beta	*t*	Beta	*t*	Beta	*t*
Constant	0.57	1.3	0.74	0.8	0.99	1.7	1.67	1.4
Destination in Manhattan (yes/no)	−1.15	−6.9	−1.61	−6.2	−0.84	−4.1	−0.97	−3.1
Estimated trip distance (km)	0.03	4.5	0.01	1.5	0.02	3.4	0.01	0.7
# of cars	0.40	4.3	0.57	3.2	0.28	2.5	0.32	1.5
Household income level (1–10)	0.09	2.5	0.28	3.5	0.06	1.3	0.24	2.4
# of workers	−0.22	−3.1	−0.46	−2.9	−0.11	−1.1	−0.21	−1.1
Neighborhood job density (10 k/sq km)	−1.61	−2.7	−2.86	−2.5	−2.15	−3.1	−3.61	−2.8
Neighborhood pop. density (10 k/sq km)	0.03	0.3	0.38	1.9	−0.04	−0.4	0.11	0.5
% of residential land (0.81 km/0.5 mile buffer)	−0.32	−1.1	−0.80	−1.4	−0.84	−2.2	−1.49	−2.0
Network dist. to subway station (km)	−0.00	−0.1	−0.03	−0.8	0.02	0.6	−0.01	−0.1
Live in N. Manhattan (yes/no, base=New Jersey)	−0.77	−1.7	−2.30	−2.8	−0.68	−1.4	−1.67	−1.8
Live in the Bronx (yes/no, base=New Jersey)	−0.57	−1.8	−1.64	−2.7	−0.31	−0.8	−1.72	−2.1
Live in Queens (yes/no, base=New Jersey)	−0.49	−1.9	−0.64	−1.2	−0.32	−0.9	−0.18	−0.3
Live in Brooklyn (yes/no, base=New Jersey)	−0.66	−2.5	−1.15	−2.2	−0.50	−1.4	−1.07	−1.6
Have access only to street parking (yes/no)	−0.58	−4.2	−0.49	−1.7	−0.67	−4.1	−0.75	−2.2
Commuting trip? (yes/no)	0.17	1.2	N/A	N/A	0.27	1.5	N/A	N/A
Sample size	1446 Trips		415 Trips		865 Trips		254 Trips	
Final log likelihood	−864.76725		−220.14343		−531.6351		−144.18009	
Adjusted rho-square	0.1049		0.2002		0.0988		0.1611	
VMT effect of parking certainty on the 1st trip leg	0.91 car km		0.99 car km		1.11 car km		1.58 car km	

for the land use, transit accessibility, and household characteristics. The odd ratios for the four models are all around 0.5 (0.57, 0.61, 0.51, and 0.47), suggesting that on-street households' odds of using cars in their trips are about half as large as the odds for off-street households. Parking certainty can have a substantial impact on households' mode choice decisions.

The certainty effect is also held for commuting trips despite its mandatory nature and inflexible travel schedule. Commuting trips are three more times likely to end up in Manhattan (32 vs. 11 percent) than non-commuting trips. Given that they are more likely to be well served by transit, any initiatives to improve the parking certainty in residential neighborhoods will likely make transit less attractive and effective. Non-commuting trips tend to be much shorter than commuting trips (7.59 vs. 13.46 km), which is more conducive to non-motorized travel such as cycling and walking. Increasing parking certainty at the home origin will counteract the many walking and cycling programs that New York City has emphasized over the past five years, such as bike lanes, bike share, pedestrianization, complete streets, etc.

To simulate the parking certainty effect on VMT, all on-street households are "offered" off-street parking space. The probability change of using cars for the same trips in the sample is calculated and multiplied with the trip distance. On average, on-street households with cars will make an extra 0.91 km in *the first trip leg* of a home-based tour, almost a 10 percent increase. The overall VMT effect on a typical weekday should be greater if all follow-up trips are counted, but the percentage increase might be similar. The increase is even higher for commuting trips (1.58 vs. 1.11 km and 0.99 vs. 0.91 km, Table 5) probably due to their relatively longer distance.

4.3. *Modeling trip frequency*

The dependent variable is the number of home-based car tours made by a household. Because tour is a count data, a linear regression model is inappropriate (Barmby and Doornik, 1989; Schmöcker et al., 2005). Other specifications, such as multinomial logit (MNL) (Wen and Koppelman, 2000), bivariate probit (Guo et al., 2007), a negative binomial regression or Poisson regression (Ma and Goulias, 1999), and ordered probit (Boarnet and Crane, 2001), are tested. The variable of interest is significant at 5 percent level in all models (and for all alternatives in the logit model). Only the negative binomial regression is presented (Table 6). Besides trip frequency, household VMT is also estimated using a linear regression model. All models are estimated for all households with cars, and on-street and driveway households only, same as the earlier mode choice models (Table 3).

In all four models, the variable of interest, whether a household only has on-street parking, is significant with a negative sign. The log count of the number of car tours for on-street households is 0.34 fewer than off-street households, and 0.30 fewer than the driveway households. Note that drive and on-street households have the same car ownership. Regarding VMT, on-street households on average make 14.3 fewer km on a typical weekday than off-street households, and 12.2 fewer km than driveway households. Such effect is consistent with the VMT gap between on-street and off-street households in Table 1.

5. Parking ease and car usage

To capture the parking ease effect, only households with multiple parking options at home are analyzed, which is almost identical to off-street households. In the study region, most off-street households do have multiple parking options at home: many garage households have a driveway in front of their garage[6], and both garage and driveway households can park on streets as well. The 269 off-street households who used their cars in the sample made a total of 469 driving-home trips. 283 trips are from the 167 garage households, and only 12 percent of them end up in a garage while 60 percent parked on the driveway and 25 percent parked on streets (Table 4). In other words, garage households were five times more likely to park in their driveway and two times more likely to park on the street than they were to park in a garage. For the 102 driveway households, the 186 trips were

[6] In the study region, not all garage households have a driveway (about 10 percent in the sample) and sometimes the driveway, especially in the form of a narrow drive alley, could not be used for parking because it could be shared by different households.

Table 3
Parking certainty, trip frequency, and VMT.

Independent variable	Households with cars				Households with cars, no garage			
	Car tours*		VMT (km)**		Car tours *		VMT (km)**	
	Beta	t	Beta	t	Beta	t	Beta	t
Constant	−1.03	−3.4	−1.25	−0.1	−1.34	−3.2	−4.78	−0.3
Household size	0.16	5.2	0.18	0.1	0.21	4.9	1.45	0.7
# of cars	0.16	4.0	12.9	5.5	0.16	3.0	14.7	4.8
Household income level (1–10)	0.05	1.9	1.15	1.0	0.04	1.3	−0.28	−0.2
# of workers	0.05	1.1	2.81	1.1	0.12	1.7	4.39	1.3
Neighborhood job density (10 k/sq km)	−1.20	−1.0	23.4	1.3	−1.95	−1.3	1.98	0.9
Neighborhood pop. density (10 k/sq km)	0.15	0.8	5.92	2.0	0.20	0.9	0.56	1.5
% of residential land (0.81 km/0.5 mile buffer)	0.31	1.6	−4.65	−0.5	0.25	0.9	−5.22	−0.4
Network dist. to subway station (km)	0.02	0.7	1.27	1.3	0.05	1.2	1.66	1.3
Have access only to street parking (yes/no)	−0.34	−3.3	−14.3	−3.3	−0.30	−2.5	−12.2	−2.2
Sample size	513 households		513 households		317 households		317 households	
Final log likelihood	−669.13721		N/A		−388.9569		N/A	
Adjusted rho-square (car tour) or R-square (VMT)	0.0832		0.1187		0.1078		0.1184	

* Negative binomial model.
** Ordinary least square regression.

Table 4
Where residents park their cars at home (unit of analysis = trips).

Parking decision parking options	In garage	In driveway%	On street%	Others %	Total trips
Garage/driveway/streets	12%	60	25	3	283
Driveway/streets	N/A	49	47	4	186
Total	7	56	34	3	469

Table 5
Travel pattern by parking location.

Parked on streets?*	Garage households (N=167)			Driveway households (N=102)		
	Yes (N=45)	No (N=122)	t	Yes (N=52)	No (N=50)	t
Car ownership	1.64	1.69	0.38	1.58	1.45	0.98
# of car tours	1.90	1.75	0.77	2.02	1.83	0.86
# of car trips	8.93	6.43	2.74	10.3	8.19	1.44
VMT (km)	61.3	45.2	2.04	57.7	42.9	1.43

* At least once on the survey day; unit of analysis = household; only households who used cars are included.

equally split between driveways and on streets. All together, 34 percent of all trips from off-street households parked on streets, as a personal choice. This result is not a surprise in the study region, where garages are normally small, located at the back of the building, and the garage door is not automatic, and where the driveway or drive alley is often narrow and often possesses physical barriers such as a gate (Fig. 1). On-street parking is often easier to use even though it requires parallel parking.

5.1. Travel pattern by parking ease (location)

For households with the same parking options, when they choose to park at different options (locations), they are subject to different levels of parking ease. Travel patterns among these households are compared (Table 5). For the 167 garage households, 45 of them parked on streets while 122 households parked on site. The two groups have a similar car ownership level, but the former tends to make 39 percent more unlinked car trips (t=2.74) and 37 percent more VMT (t=2.04), suggesting a strong parking ease effect. For the 102 driveway households, those who parked on streets tend to make more car tours and have higher vehicle miles, but the differences are not significant. This suggests that the easement level between street parking and driveway parking might be similar.

Table 6
Parking duration by parking type.

Group comparison	Parking duration time (min)*	Mean difference (min)	t
On-street vs. off-street	94 vs. 125	31	−2.66
On-street vs. garage	94 vs. 139	45	−2.27
On-street vs. driveway	94 vs. 104	10	−0.49
On-street vs. parking lot	94 vs. 163	69	−2.42

Source: 813 car trips from 497 households (out of 10971 in the entire NYMTC survey) with garage: 46 trips parked on streets, 419 trips parked in garage, 316 trips parked in driveway, and 32 trips parked on parking lot.
* Non-overnight parking only.

To further understand why parking at different locations affects car usage, the parking duration time at different parking locations is examined. Such an analysis requires a much larger sample because overnight parking should be excluded and only households who made at least two car tours on the survey day can produce at least one observation of non-overnight parking at home. Therefore, the entire NYMTC survey for 10,971 households in the whole metropolitan region is used. However, it is impossible to identify the parking options for all these households, so only a portion of garage households are analyzed if they reported parking in garages. Note that not all garage households used their garage in the survey, and there is no way to identify either on-street or driveway households because a household who reported parking in driveway may also have a garage. Such a process yields only 497 garage households with 813 trips that do not end up with overnight parking. These trips parked at different parking locations such as garages, driveways, and parking lots, and the average durations of parking are compared. The results are summarized in Table 6.

As shown, the average parking duration on streets is 94 min, 31 min shorter than the parking duration at off-street and significant (t=2.66). The gap is the greatest between parking on streets and parking in a parking lot at 69 min (t=−2.42), followed by garage parking at 45 min (t=−2.27) and driveway parking at only 10 min (t=−0.49). In other words, cars parked on streets have

Table 7
Home-based car tour generation for households with garage.

Specification=multinomial logit	All home-based car tours (base=1 tour)			
Independent variable	2 Tours		3 or more tours	
	Beta	*t*	Beta	*t*
Constant	−4.13	−3.7	−6.22	−4.3
Household size	0.25	1.4	0.37	1.8
# of cars	1.01	3.1	1.44	3.8
Neighborhood job density (10 k/sq km)	4.43	1.6	4.39	1.1
Neighborhood pop. Density (10 k/sq km)	−0.61	−1.1	−1.92	−2.5
% of residential land (0.81 km/0.5 mile buffer)	1.84	2.0	2.45	2.2
Network distance to rail station (km)	0.03	0.5	0.01	0.1
Car parked on streets before trip starts (yes/no)	0.46	0.3	3.94	2.1
Generalized residual of parking on streets	0.12	0.1	−2.28	−1.9
Number of observations	147 households with garages who made at least one home-based car tour on the survey day.			
Final log likelihood	−124.39086			
McFadden Pseudo R Square	0.1761			
Parking ease effect	0.136 tours			

Note: # of households: 1 tour=73, 2 tours=46, 3 or more tours=28.

a higher frequency of usage. The results suggest that when garage households park on streets instead of the garage, they tend to make more car tours than otherwise. However, this relationship is only association not causality. As discussed earlier, endogeneity may exist; for example, if a resident decides to use the car again, she or he may simply park on the street and not bother to pull the car into a garage. In this case, the resident makes more car tours not because of the ease of parking at a particular location but because of an earlier decision dictated by other factors. Without controlling for this endogeneity, the effect of parking design on car usage will be biased.

5.2. *Modeling trip frequency after controlling endogeneity*

Because parking in the driveway and on the street seem to have a similar level of parking ease, this analysis targets the garage households between parking on streets and parking in garage and driveway combined. Note that about a third of garage households do not have a driveway or parking yard at the front of the building to park the car. They have to either park on streets or move cars to the garage at the back of the building.

Again, garage households who parked and who did not park on streets on the survey day have the same car ownership level (Table 5). The dependent variable is the number of home-based car tours, with the basis for comparison being one home-based car tour. The variable of interest is whether a garage household parked on the street or not.

The instrumental variables, together with control variables in the tour generation model, are used in a probit model to predict the probability of a household parking on streets. The generalized residual, instead of the predicted value, is added, not replacing the endogenous explanatory variable, to the main model. The first stage probit model is listed in Appendix A. Various model specifications are tested, and only the MNL models are presented here (Table 7), because it allows analysis at both the overall and different tour levels. The generalized residual is only significant at the 10 percent level and for the alternative of three or more tours. This suggests that weak endogeneity may exist but only for households who make frequent tours, which is understandable. The variable of interest, whether a garage household parked on the street on the survey day, is significant for three or more tours. When garage households park on streets instead of off-street, they tend to use cars more frequently, even after controlling for the potential endogeneity in the decision process.

Alternative models are also estimated. The multinomial probit model is able to produce the same results (almost the same *t* values). A zero truncated Poisson regression is estimated because all garage households in the sample made at least one car tour, and no overdispersion is found in the data. An ordered probit is also estimated. In both models, the variable of interest, parking on streets, is only significant at the 10 percent level. Further studies are necessary in order to confirm the parking ease effect on car usage.

To illustrate the scale of the parking ease effect on households' tour generation, a hypothetical policy that bans street parking for households with a garage was simulated. Now all households have to change their parking behavior and park off-street. The average number of tours decreases from 1.79 to 1.66 per household, a reduction of 0.133 tour (7.5 percent)[7] . In other words, if on-street parking is prohibited, one out of thirteen home-based tours from garage households would be eliminated. Because the average vehicle miles traveled per tour for these households is 27.8 km, this reduction corresponds to 2.08 km per household per weekday. This estimation is preliminary because the eliminated tours might be shorter than the average 27.8 km and households may combine multiple tours into one to mitigate the parking ease effect while not reducing the total VMT. Nevertheless, it provides an approximate scale of the impact of parking ease on trip making.

6. Policy discussion

The above results indicate that parking convenience at the home origin indeed matters to households' car usage. When parking is guaranteed back home, households are more likely to drive cars instead of using other modes, make more car trips, and travel longer vehicle miles. When the parking place is easy to maneuver in and out, households are inclined to use cars more often. Such a convenience effect is not trivial. The parking certainty effect is approximately 10 percent of a household VMT for car-owning on-street households, while the parking ease effect is about 7.5 percent for all car-owning garage households who used cars on the survey day. The first effect corresponds to approximately 0.8–1.1 million households in the five-county area right outside Manhattan, who travel an average 42.3 km per weekday[8] . If these on-street households were granted

[7] Note that this simulation is based on both the significant relationship with 3+ tours and the insignificant relationship with 2 tours in Table 7. The original coefficient for the 2 tours and zero (because it is insignificant) are used in the simulation and yield similar results because the original coefficient is quite small.

[8] The five counties are Queens, Kings (Brooklyn), and Bronx in New York, and Hudson and Bergen County in New Jersey. Bergen County has a large, lower density

guaranteed parking at home, their VMT would increase by 3.25–4.55 million km every weekday. The second effect corresponds to about 1.7–2.0 million garage households in the five-county area with an average VMT of 31. If street parking becomes unavailable, their VMT would reduce by a total of 6.5–7.5 million km every weekday. Therefore, the total convenience effect on car usage in the study region probably ranges from 9.75 to 12.05 million km every weekday. The accuracy of these numbers needs to be tested in further studies. However, their scale indicates that parking convenience cannot be overlooked in the parking policy decisions.

How could these results shed light on current residential parking policies? Four policy examples are examined from the parking convenience perspective: the minimum off-street parking requirement, resident parking permits, street cleaning, and the new urbanism neighborhood design principles. The first is for off-street parking, the 2nd and 3rd for on-street parking, and the last one is for both on-street and off-street parking.

The minimum off-street parking requirement has been criticized from multiple fronts such as reduced housing affordability, subsidized car ownership, degraded streetscape, etc. (Shoup, 2005). The parking certainty effect further suggests that applying this policy to infill developments in a dense urban setting will result in a significant increase of car usage (even when car ownership is fixed). Many residential buildings in a dense urban setting like the study region do not have on-site parking, and many residents rely on streets to park their cars. Off-street parking must cut the curb and normally remove one or two street parking spaces away from the stock. The net gain of (off-street and on-street) parking could be very limited in such a setting. For example, a survey in Mission District, a 40-block neighborhood in downtown San Francisco, found that curb cuts take 30 percent of the total curbside length, and result in a combined total loss of 356 out of 878 potential on-street parking spaces. Since there are only 883 cars registered in the neighborhood, all but five of them could have parked on the street simultaneously if garages and curb cuts had not been added (Brown, 2007). In other words, the minimum requirement is essentially “converting” on-street parking into off-street parking in this neighborhood. Since parking certainty is improved, households are likely to drive more.

Another negative aspect of the minimum requirement is that even though the overall parking space is increased due to the off-street parking requirement, the total parking capacity might still decline. On-street parking is shared parking and in general more efficient than off-street parking in meeting parking demand, just like comparing a taxi cab with a private car in meeting travel demand. In a report done by the UK Department of Communities and Local Government (2007), 13 percent more parking spaces is required to meet the same level of parking demand if all parking spaces are provided off-street on each property instead of as shared parking on streets, because different households have different level car ownerships. Therefore, from the parking certainty perspective, it might be necessary to treat street parking with a higher priority than off-street parking in an urban setting. When all parking demand could be met by street spaces, off-street parking could be cut back or even is not required. One typical example is the Crown Street project in Glasgow, Scotland, a large residential development with 2050 units that has accommodated all parking on streets (U.K Department for Transport (U.K DfT), 2007).

The parking convenience effect also helps understand the behavioral consequences of regulating street parking in a dense urban setting. For example, although resident parking permits may prevent parking intrusion from non-residents and reduce possible parking cruise by residents, they may improve the parking certainty for local residents and therefore encourage car usage. Street cleaning makes street parking temporarily unavailable to local residents. To garage households, it means that they have to park cars in the relatively inconvenient garage instead of on streets, which may discourage them from using cars. Indeed, a study by Guo and Xu (2013) found that street cleaning in the New York City area reduced the number of car trips made by off-street households by a noticeable 1.2 percent. Such an effect may be applicable to other dense urban settings with a frequent schedule of street cleaning.

Lastly, the parking ease effect may help understand the behavioral consequence of some new urbanism design principles. In many conventional suburban communities, residential streets are often excessively wide with abundant street parking. Garages dominate the building front, directly facing street with wide doors. According to this research, all these design features are conducive to parking, and likely encourage car usage. In contrast, many new urbanism communities often reduce the minimum street width requirement and provide narrower streets with more strict regulations over street parking. Many restrict the size and location of garages to make them less protruding. Some put garages to the back of the house connected with narrow alleys. Carmel, California, limits the width of all garage doors that face a street for a single car (Mukhija and Shoup, 2006). If the garage has more than one space, cars will be parked in line instead of in parallel, which makes parking more complicated. All these features are advocated primarily for economic and aethestic reasons, but according to this research, they may also have a strong impact on travel outcomes. Of course, these communities might be very different from the study region in terms of density and transit accessibility. Whether such behavioral consequence is true or not can only be confirmed with further empirical studies.

Appendix A. Model of garage households parking on street (First Stage Model).

Specification = probit	Parked on street? (yes/no)	
Control variables	Beta	*t*
Constant	−0.58	−0.6
Household size	0.24	2.7
# of cars	0.04	0.3
Neighborhood job density (10 k/sq miles)	−10.26	−2.0
Neighborhood pop. density (10 k/sq miles)	1.62	2.1
% of residential land (0.5 mile buffer)	0.10	0.2
Network distance to rail station (miles)	−0.12	−1.8
Instrumental variables		
Single family detached (yes/no)	0.17	0.5
Single family attached (yes/no)	0.55	1.4
Property ownership (yes/no)	−0.81	−2.8
Garage in the backyard (yes/no)	−0.40	−1.3
Alternative parking near street on the property (yes/no)	−0.41	−1.7

(*footnote continued*)
area not included in the study region, so the percentages from the sample are applied as a range. For example, although the percentage of car-owning households who only have on-street parking is 34.8 in the sample, I used both 34.8 and a lower value 25 to estimate all car-owning households with only on-street parking in the five-county area. All the average VMT estimates are obtained directly from the original NYMTC survey instead of the sample of 840 households. All the numbers are an approximation and may not be precise enough, but they offer sufficient information about the scale of the effect.

Physical barrier to garage exists (yes/no)	0.33	1.9
Number of observations	147 Garage households	
Final log likelihood	−71.6045	
McFadden Pseudo R Square	0.1858	

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