Comparison of Mode Cost by Time of Day for Nondriving Airport Trips to and from New York City's Pennsylvania Station

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A novel methodology used taxi global position system data and high-resolution transit schedule information to compare travel times and travel fares of the two main nondriving travel modes for airport ground access: taxi and transit. Five origin–destination pairs between Pennsylvania Station in New York City and three airports in the New York region were used as an example to demonstrate these methods. An analysis of total trip cost considered both travel time and expenditures on fare. A binary logit model was used to model the mode choice of travelers. The results indicate that transit is the more likely choice during most of the day except the midnight period when transit service has longer headways. A sensitivity analysis shows the relationship between the value of time and total trip cost per passenger for different numbers of passengers traveling together and at different times of day. The higher the value of time and the number of passengers in a group, the more likely it is that a taxi is chosen for airport trips. The attractiveness of one mode relative to the other varies spatially and temporally according to the travel time and price. This paper focuses on understanding temporal variation of total cost of each mode and the effect that this variation is likely to have on mode share.

Transportation planning for airport ground access has attracted increasing attention in recent years from both planners and researchers. Approximately 65% of airport trips are made by private vehicles in the United States and Europe (*1*). The remaining 35% of trips depend on alternative airport access modes. For example, 37% of the passengers leaving John F. Kennedy International Airport (JFK) in New York City are estimated to use taxis (*2*). Several studies have been conducted to measure the effectiveness of airport ground transportation services other than private automobiles, such as taxicabs, buses, or trains, based on the speed and reliability of travel times for these alternative modes (*3, 4*). Another challenging issue is to understand air passengers' airport access mode choice. Trips to and from airports should be treated separately in regional behavioral travel models because of their unique characteristics (e.g., different value of time for passengers) and a number of factors that influence mode choice, such as trip purpose (e.g., business or leisure) and time of day (*5*). The trip cost of using an alternative mode relative to driving has been shown to be one of the major factors affecting the mode choice of passengers along with factors such as the frequency of service and luggage capacity (*6*).

The generalized cost of travel for different modes of transportation varies significantly depending on several factors related to traffic conditions and public transportation schedules. The use of public transportation might save money, but in return people give up the convenience of a door-to-door ride directly to or from their home or workplace. The willingness to pay for more reliable transportation service for airport access is estimated to be considerably higher than for regular daily commutes because scheduling constraints are more binding (*5*). Estimated values of time for airport trips have also been found to be significantly different than estimated values for overall network travelers (*5*). Moreover, shorter travel times are valued more for business trips compared with nonbusiness trips to avoid the risk of missing the flight (*7*).

This study is motivated by the importance of realistically comparing travel costs of alternative modes for airport ground access using revealed data sources. The majority of studies in the literature calculate the transit trip costs using previously determined schedules for certain types of transit services, which cannot address all of the available transit options for airport ground access in cities with highly complex transit networks such as New York City. Different transit options for different times of day should be considered in the analysis, because the speed and reliability of each mode vary over the course of a day. While some of the existing methodologies consider waiting times as a part of total travel time, rough estimates for possible transfer times at train or bus stations can lead to biased results. It has also been demonstrated that about 40% of the population in the United States uses smartphones, and there is a great potential for these devices to disseminate reliable real-time transit travel information (*8*). Taxi travel times, however, are usually calculated assuming that the vehicle travels on the shortest path to the airport. Traffic conditions on the network by time of day have not been addressed adequately in previous studies, although traffic congestion affects both the travel time and taxi fare.

This study uses a novel methodology utilizing big data to compare travel times and fares for New York City airport ground access by taxi and transit. The analysis is based on historical taxi GPS data recordings in New York City and transit schedule information from a web-based application that was developed with Google Maps Developer Application Programming Interface (API). The transit travel time data enable users to compare the travel times for a transit

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passenger who uses his or her smartphone to plan an airport trip. Taxi travel times, on the contrary, are the average values by hour of the day of the observed trips that are extracted from the New York City taxi GPS data. Therefore, the comparison in this study aims to evaluate the travel options available to a well-informed passenger, who has perfect knowledge about the expected taxi fare and travel time.

This paper is organized as follows. The literature review gives a summary of findings from previous studies on airport mode choice and related ground access studies. The next section describes the data, followed by a section explaining the methodology used for the comparative analysis. A conclusion summarizes the findings.

LITERATURE REVIEW

A significant body of research has been developed to understand how individuals choose to access airports. Harvey's study was one of the first studies to demonstrate the factors influencing the airport access mode choice of departing airline passengers on the basis of a travel survey in the San Francisco Bay Area in California (*9*). The analysis, using a multinomial logit model, shows that travel time and travel cost are two strong explanatory variables. Business travelers are found to be more sensitive to airport access travel time than leisure travelers, and values of time for most individuals are estimated to be at least as high as the average wage. Extra luggage, which is defined as more than one piece per person, deters passengers from choosing transit (*9*). Psaraki and Abacoumkin analyzed the mode split for Athens International Airport in Greece to predict future mode shares and found that international passengers are more likely to use taxis or be dropped off by private cars (*10*). Pels et al. also studied mode choice in the San Francisco Bay Area and reported that business travelers have higher value of time and higher access time elasticity compared with leisure travelers (*11*). The authors reported that access time has a larger influence on mode and airport choice compared with the dollar cost. However, they calculated travel times for each alternative mode as follows: public transit travel time estimates are drawn from train and bus schedules, and taxi travel times are based on distances from the center of the origin zip code to the airport. Therefore, their estimations do not account for walking and transit transfer times for public transit or the effect of traffic congestion or road network circuity for taxis or private vehicles.

Some studies have investigated the factors that influence airport ground access mode choice, including demographics, trip cost, travel time, travel time reliability, and accessibility. Gupta et al. developed a ground access mode choice model for New York City using an air passenger survey and a nested logit model (*5*). They prepared transit level of service data exogenously using online schedules, and waiting times were also taken into account. Demographic characteristics, trip cost, travel time, and trip purpose are shown to be the most significant variables in passengers' mode and airport choice, which is consistent with previous studies. Tam et al. investigated how travel time reliability affects mode choice, using a combined data set from revealed and stated preference surveys (*12*). The authors state that increasing reliability can attract more passengers to use bus services. Luken and Garrow studied the airport choice problem in New York City (*13*). Their analysis, based on online ticketing data, showed that the accessibility of the airport significantly affects the airport choice. They acknowledge that their model can be improved by explicitly considering peak and off-peak driving times.

The analysis presented in this paper is unique in several ways. First, this study considers costs by time of day, which has not been considered in detail in the existing literature. Real data for peak and off-peak time periods provide useful information about how the generalized costs of different alternatives change by time of day. Second, this study uses two novel data sets for this domain: records of 10 months of taxi GPS data provide accurate distributions of taxi travel times by time of day, and detailed travel times by transit based on transit schedules are acquired from Google Maps API. The analyses are made from the perspective of a passenger who considers his or her options with respect to dollars and time before making an airport trip.

METHODOLOGY

The objective of this study was to develop a data-oriented method to compare the generalized cost for different nondriving modes for airport access and to understand whether transit or taxi yields a better utility at different times of the day. While the results of this study may be useful to individuals making travel choices, the method proposed in this study can also help policy makers understand the factors that affect mode choice so that they can plan airport ground access.

As web services and information technology become more advanced, it is easier for people to acquire complete information about travel by transit and taxi. Assuming that passengers make travel decisions based on money costs and travel time, the relative attractiveness of one mode over the other may change as transit schedules, fares, and taxi travel times vary for different times of day and days of the week. The relevant information can be obtained from Google Transit and a large set of taxi GPS data.

The total generalized cost for an individual trip in units of dollars can be computed for each mode i at time j and is denoted by TC_{ij}. The value of TC_{ij} is calculated as follows (*14, 15*):

$$\mathrm{TC}_{ij} = \alpha \times T_{ij} + \frac{F_{ij}}{n} \tag{1}$$

where

α = passenger's value of time (\$/h),
T_{ij} = average travel time for the trip (h),
F_{ij} = average fare paid for the trip (\$), and
n = number of passengers sharing a taxi cab (for transit $n = 1$).

The total generalized cost can also be expressed in units of hours by dividing the TC_{ij} value by α. The utility of travel by mode i (i = tran for travel by public transit and i = taxi for travel by taxi) at time j is denoted by U_{ij}. This utility is based on the total generalized cost, which can be derived from the travel time and fare, as follows:

$$U_{\mathrm{tran},j} = b - \beta \times \mathrm{TC}_{\mathrm{tran},j} = b - \alpha\beta \times T_{\mathrm{tran},j} - \beta \times F_{\mathrm{tran},j} \tag{2}$$

$$U_{\mathrm{taxi},j} = b - \beta \times \mathrm{TC}_{\mathrm{taxi},j} = b - \alpha\beta \times T_{\mathrm{taxi},j} - \frac{\beta \times F_{\mathrm{taxi},j}}{n} \tag{3}$$

where b is the benefit for each individual of completing a trip to or from the airport, and β is the equivalent utility of a dollar. For an airport trip, the benefit is assumed to be the same for both choices as long as the origin–destination (O-D) pair is fixed. The choice between two modes, such as transit and taxi, is typically modeled with a binary logit model based on the difference of utilities between the choices (*16*). The probability that an individual will choose transit over taxi ($P_{\text{tran},j}$) is

$$P_{\text{tran},j} = \frac{e^{U_{\text{tran},j}}}{e^{U_{\text{tran},j}} + e^{U_{\text{taxi},j}}} = \frac{e^{(-\beta \times \text{TC}_{\text{tran},j})}}{e^{(-\beta \times \text{TC}_{\text{tran},j})} + e^{(-\beta \times \text{TC}_{\text{taxi},j})}} \tag{4}$$

and the probability of choosing taxi over transit ($P_{\text{taxi},j}$) is

$$P_{\text{taxi},j} = 1 - P_{\text{tran},j} \tag{5}$$

The number of passengers choosing mode i is the product of $P_{i,j}$ and the total travel demand. In the following sections, transit and taxi trips in New York City are compared on the basis of their travel time, total cost, and the corresponding choice probability.

CASE STUDY

The two main types of public transportation services for airport access in New York City, transit (including train, AirTrain, subway, and bus) and taxi, are compared for trips between Pennsylvania (Penn) Station and the three main airports in the New York region (Figure 1): JFK, Newark Liberty International Airport (EWR) in New Jersey, and LaGuardia Airport (LGA) in New York. These three airports constitute the largest airport system in the United States. Penn Station was selected as the nonairport trip end of interest for this study because it is a major hub of transit and taxi activity. The 10-month data set contains 1,460 observed trips from Penn Station to EWR Airport, which is 18% of all trips from Penn Station that leave New York City. From Penn Station, there were 16,152 observed trips to and from JFK Airport and 25,673 trips to and from LGA Airport, which constitute roughly 1% of all taxi trips that start or end at Penn Station. The accessibility through transit, taxi, or car for all airports is as follows (*17*):

- JFK Airport, located in Queens, New York, is accessible from AirTrain, buses, cars, and taxis. AirTrain JFK connects to the Long Island Rail Road and the New York City subway and bus system at Jamaica and Howard Beach, New York.
- EWR Airport is located in Newark, and is accessed from Manhattan via the Holland and Lincoln Tunnels by car or taxi. AirTrain Newark provides access to New Jersey Transit trains into New York City.
- LGA Airport, located in Queens, New York, is 4 mi from Manhattan and can be accessed by car or taxi. LGA Airport does not have a direct rail link, but bus service does connect to the Long Island Rail Road and subway.

Taxi Data

Taxi GPS data for New York City were available for every trip in a 10-month period (February 1, 2010, to November 28, 2010). The

FIGURE 1 Locations of New York City's Pennsylvania Station and three airports (NYC = New York City; NJ = New Jersey).

data consisted of 147 million taxi trips across the city, from which trips between Penn Station and the three airports were extracted. New York City taxi trip data have also been used in studies of travel time reliability for inner-city traffic (*18*) and commercial vehicle delivery time estimation (*19*).

The data set has 30 fields for each taxi trip with detailed taxi-specific information (e.g., medallion number, shift number, driver name), temporal and spatial information (taxi pickup and drop-off date, time, location), fare (e.g., toll, tip, total fare paid), and distance traveled. All airport trips within a 500-ft (152-m) radius of the center of Penn Station and a 1-mi (1.61-km) radius of the center of EWR Airport and within the census tract of JFK Airport (census tract ID 36081071600) and LGA Airport (census tract ID 36081033100) were considered. Because New York City taxis are not allowed to pick up passengers from EWR Airport, no taxi trips were available from EWR Airport to Penn Station during this period, so only trips from Penn Station to EWR Airport were included in this study. JFK and LGA Airports have taxi trips in both directions, so a total of five O-D pairs are considered and summarized in Table 1.

The total fare is a flat rate between most of Manhattan and the airports at JFK or EWR plus any tolls, tips, and surcharges. The fare between Manhattan and LGA (Airport) has some variability because trips are charged the normal metered rate. The travel time has largest variability among all four variables, which indicates variability of traffic conditions. The trip distance is mostly stable for all airport trips, but the slight variability indicates that various alternative routes might be taken for the same O-D pairs.

Transit Data

Google Maps API Transit Directions Service, which offers free transit route guidance with a daily request limit, was used to obtain transit data. The information was gathered in XML format using a web-based JavaScript code. An application was developed that extracts 1 week of travel time and route information (including weekdays and weekends) on the basis of schedules for the five O-D pairs every 5 min throughout the day. The routing information provided by Google is assumed to be the optimal transit option for the requested time and O-D pair because the web-based routing service compiles all available scheduling information for different transit modes and routes. The fare is estimated on the basis of the optimal route.

Data for approximately 2,016 transit trips were collected for each O-D pair. The transit travel duration of each trip included waiting time, transfer time, and in-vehicle travel time. The transit travel time distributions for all five O-D pairs are shown in Figure 2, indicating that travel times on weekdays are consistent, possibly because the transit schedule is similar for all weekdays, but it is necessary to analyze travel times on Saturday and Sunday separately. The average travel times for transit on weekends are higher because service headways are longer, and average travel times for taxis on weekends are lower because traffic is less congested. The day of the week affects the costs that travelers face on each mode.

Determination of Value of Time, α

The value of time for airport trips varies considerably from person to person, and it can be considered as a continuous random variable that is distributed across the user population (*20*). The value of time for business trips can be higher than for leisure trips (*5, 9*). The distribution of values of time for airport trips is also likely to differ from that of other trip purposes, which makes estimation of this value difficult.

The UK Department of Transportation suggests £47.95 (equivalent to US$76) as the value of time for a taxi or minicab passenger and £39.65 ($63) for a rail passenger in 2010 (*21*). For trips to and from Penn Station, the income in Manhattan is used as a reference value (*9*). The 5-year (2007 to 2011) American Community Survey estimate of per capita income in Manhattan is $61,290 (*22*), which is $29.5/h if working a full-time job with 40 h/week. Gupta et al. considered a higher value of time for airport trips because travelers may be willing to pay more to avoid missing their flight (*5*). The authors suggested values of $42/h for leisure trips and $63/h for business trips. Since the value of time for passengers who made airport trips in New York City was not known, a preliminary value of time of $40/h was used to represent everyone and anytime on the basis of the above references. In the sensitivity analysis that follows, wide-ranging values of time are considered.

Calibration of Coefficient β

Equation 2 describes the relationship between cost and utility, and the β-coefficient plays an important role in determining the outcome

TABLE 1 Taxi Trips Extracted from 10-Month GPS Data and 1-Week Transit Trips

		Taxi				Transit	
O-D Pair	Number of Observations	Passenger Number [Mean (SD)]	Total Amount ($) [Mean (SD)]	Trip Time (min) [Mean (SD)]	Trip Distance (mi) [Mean (SD)]	Trip Time (min) [Mean (SD)]	Fare ($) [Mean (SD)]
Penn–JFK	5,624	1.81 (1.29)	52.34 (5.26)	47.79 (17.57)	17.24 (1.89)	52.51 (10.34)	12.47 (1.69)
JFK–Penn	2,691	1.87 (1.27)	51.69 (4.33)	45.11 (12.74)	17.72 (1.79)	60.96 (10.03)	12.65 (1.37)
Penn–LGA	9,697	1.63 (1.21)	34.85 (5.64)	31.43 (10.30)	10.23 (1.38)	60.85 (6.32)	4.92 (3.57)
LGA–Penn	3,630	1.65 (1.22)	35.07 (5.58)	32.06 (9.35)	10.21 (1.71)	61.48 (7.57)	6.91 (3.23)
Penn–EWR	1,445	1.80 (1.28)	67.30 (10.48)	32.09 (9.49)	17.08 (2.05)	58.87 (19.90)	17.25 (9.54)

NOTE: SD = standard deviation.

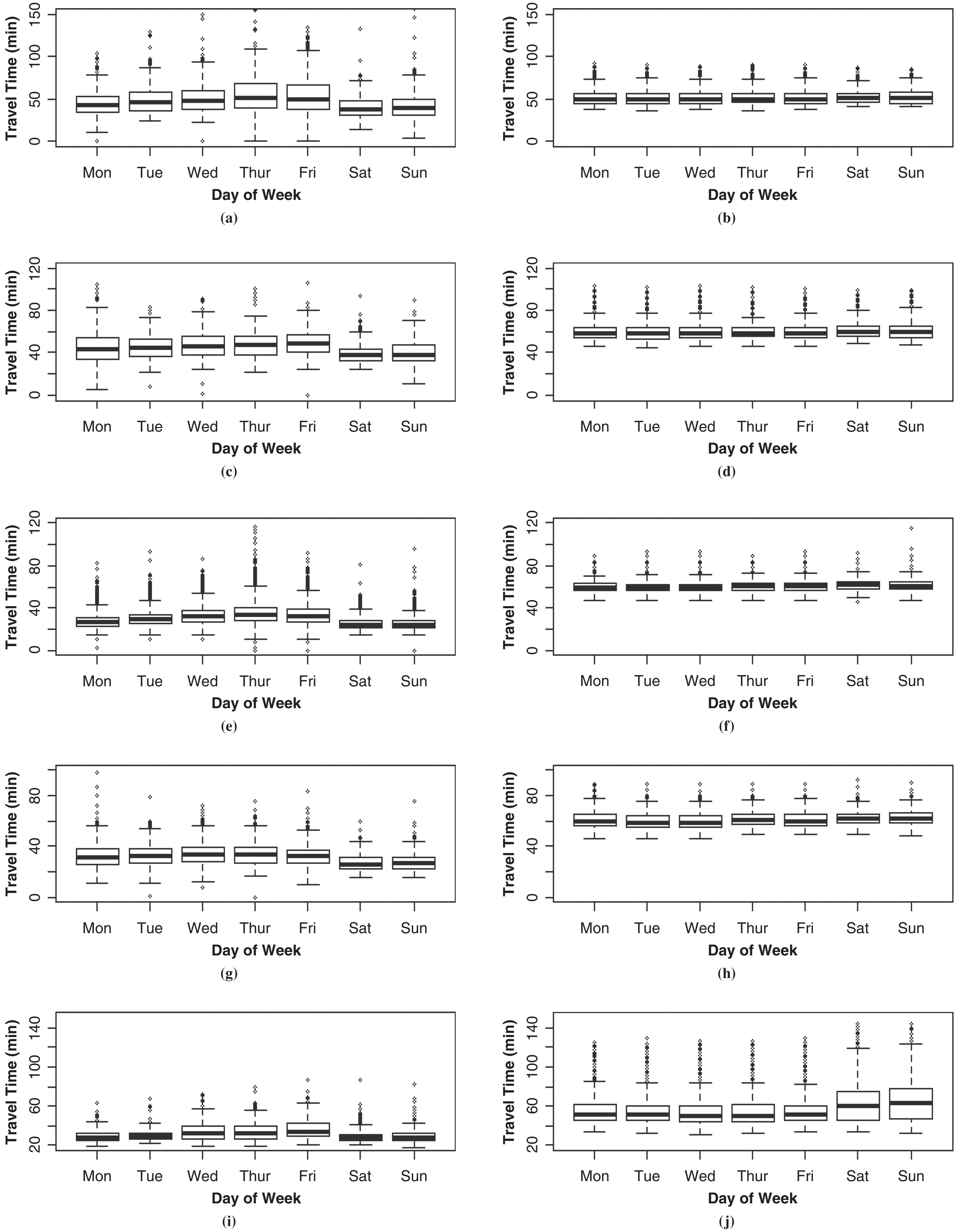

FIGURE 2 Box plot of transit travel time by day of the week for five O-D pairs: (*a*) taxi time and (*b*) transit time from Penn Station to JFK Airport, (*c*) taxi time and (*d*) transit time from JFK Airport to Penn Station, (*e*) taxi time and (*f*) transit time from Penn Station to LGA Airport, (*g*) taxi time and (*h*) transit time from LGA Airport to Penn Station, and (*i*) taxi time and (*j*) transit time from Penn Station to EWR Airport (Mon = Monday; Tue = Tuesday; Wed = Wednesday; Thur = Thursday; Fri = Friday; Sat = Saturday; Sun = Sunday).

of the binary logit model. The β-value is the marginal utility of total cost. To estimate mode choice, it is necessary to determine β, which can be done by comparing the total number of transit and taxi trips. JFK AirTrain ridership information and taxi GPS data are used to estimate a single β value. One value of β is used for all three airport trips because it is likely that the average marginal utility of total cost is similar for passengers using each of the airports. Furthermore, data are not available to estimate specific β-values for LGA and EWR Airports.

Paid ridership on the JFK AirTrain was 5.3 million passengers in 2010 (*23*), which accounted for nearly all of the transit trips to and from JFK Airport. In the same time period, there were 3.386 million taxi trips to and from JFK Airport, extrapolated from the complete 10-month records of taxi GPS data. On the basis of the trip counts above, 39% of nondriving trips were made by taxi and 61% were made by transit to get to and from JFK Airport.

Without more detailed transit ridership data, the overall mode share for all trips to and from JFK Airport during 2010 is considered to be the same as the mode share for trips between Penn Station and JFK Airport. The logit model is calibrated by selecting the β-value that makes the model estimates over the course of the day match this observed mode share, assuming that $n = 1$ and $\alpha = \$40/\text{h}$. At each hour, the relationship between number of taxi trips ($n_{\text{taxi},j}$) and the estimated number of transit users ($\hat{n}_{\text{transit},j}$) is

$$\frac{n_{\text{taxi},j}}{P_{\text{taxi},j}} - n_{\text{taxi},j} = \hat{n}_{\text{transit},j} \qquad (6)$$

$$P_{\text{taxi},j} = \frac{\Sigma_j n_{\text{taxi},j}}{\Sigma_j \hat{n}_{\text{transit},j} + \Sigma_j n_{\text{taxi},j}} \qquad (7)$$

When $\beta = 0.012$, the expected probability of people choosing a taxi to the airport is 0.39, which matches the data from 2010. This value of β is applied to the cost data for all the airport trips to estimate the mode share by taxi and transit.

Assumptions and Data Processing

In this study, the main challenges were the data collection and data processing. Some assumptions made to perform the comparison of transit versus taxi use are as follows:

- Taxi fares are calculated per person, so the total fare is divided by the number of passengers, but the travel time is experienced by each passenger regardless of the group size.
- There are always a sufficient number of taxis available at each airport for passengers to hail, so no time is spent walking and waiting for a taxi at any airport.
- The origin and destination of the transit trips are very close to the transit stops, so the walking distance is negligible.
- The average trip duration in an hour of the day is assumed to represent the travel time at that hour of the day for both train and taxi, provided that there are many trips per hour.
- All passengers are able to buy the tickets before boarding transit to avoid additional fees. Metropolitan Transportation Authority subway and bus riders pay a flat rate of $2.50 per trip. Discount fares, such as senior citizen ticket, weekly tickets, or monthly tickets, are not considered.
- Travelers to all airports are assumed to have the same average utility preferences, so β is the same for all trips.

The deficiencies in GPS data, mostly resulting from satellite errors, receiver noise errors, coordinate transformation errors, and errors made by the driver, need to be filtered (*24*). The taxi GPS data were processed to minimize the influence of outliers. Some false records were eliminated, for example, records that had total fare amount equal to zero or had a travel distance less than the straight-line distance between the origin and destination. Sometimes more than two criteria were used to determine whether to remove a data point (e.g., fare amount, distance, and travel time). Ultimately, less than 2% of the original taxi records were eliminated through this filtering process. This data selection procedure requires familiarity with information such as fare amount, distance between Penn Station and each airport, travel time, and the rate codes.

Transit data collected from Google every 5 min for all three airports were kept without filtering because Google estimates were already based on clean schedule data. The transit fare was calculated according to the routes that Google Maps provided at different times of the day.

Results

On weekdays, the average travel time for taxis is less than that of transit at all times. When considering both the time and money spent on the trip, the total cost indicates that even if the passenger is traveling alone, taxi has a cost advantage only in the middle of the night (midnight to 6 a.m.). The taxi travel times vary significantly, and the longest travel times are usually observed during morning peak hours (6 to 10 a.m.) and afternoon peak hours (2 to 6 p.m.) as shown in Figure 3.

To consider the variability of travel costs, the standard error (SE) is calculated for the total cost of trips (shown with error bars in Figure 3). Some taxi data have few observations at midnight, which results in a relatively higher SE and a wider 95% confidence interval for the mean values at each hour (approximately equal to mean $\pm$ 1.96 $\times$ SE). Conversely, the transit data show relatively small variance within each of the 24 h. The main difference in transit travel times arises from the waiting times and transfer times for the next available train or bus. The transit travel time and cost are less variable than taxi travel time and cost, which depend on the traffic condition at different times of day and from day to day (*12*).

This analysis was limited to trips between Penn Station and the three airports. The probability of choosing taxi at each time of day was calculated by using the binary logit model, and the results are plotted in Figure 4. On the basis of the difference of total cost for taxi and transit, the mode share can be expected to change for different times of the day. For example, transit tends to be more competitive during peak hours when traffic congestion makes taxi trips slower. Conversely, taxis are more competitive in late-night hours when transit headways are long.

Because these O-D pairs are just a partial set of all trips that go to and from the airports, the analysis only reflects the costs at those locations. Different locations may have a totally different trend based on the travel time and cost. Time and money are not the only things that people consider when making travel choices, but the literature suggests that these are the most important factors. It is possible that some people use transit for all trips without even considering taxis, or others take taxis to the airport without ever considering the transit trip.

Some factors that likely influence mode choice other than travel time and fare are that taxis provide a more personalized door-to-door service with additional benefits, such as assistance with luggage. Some of this value is captured in the tips that are included in the taxi

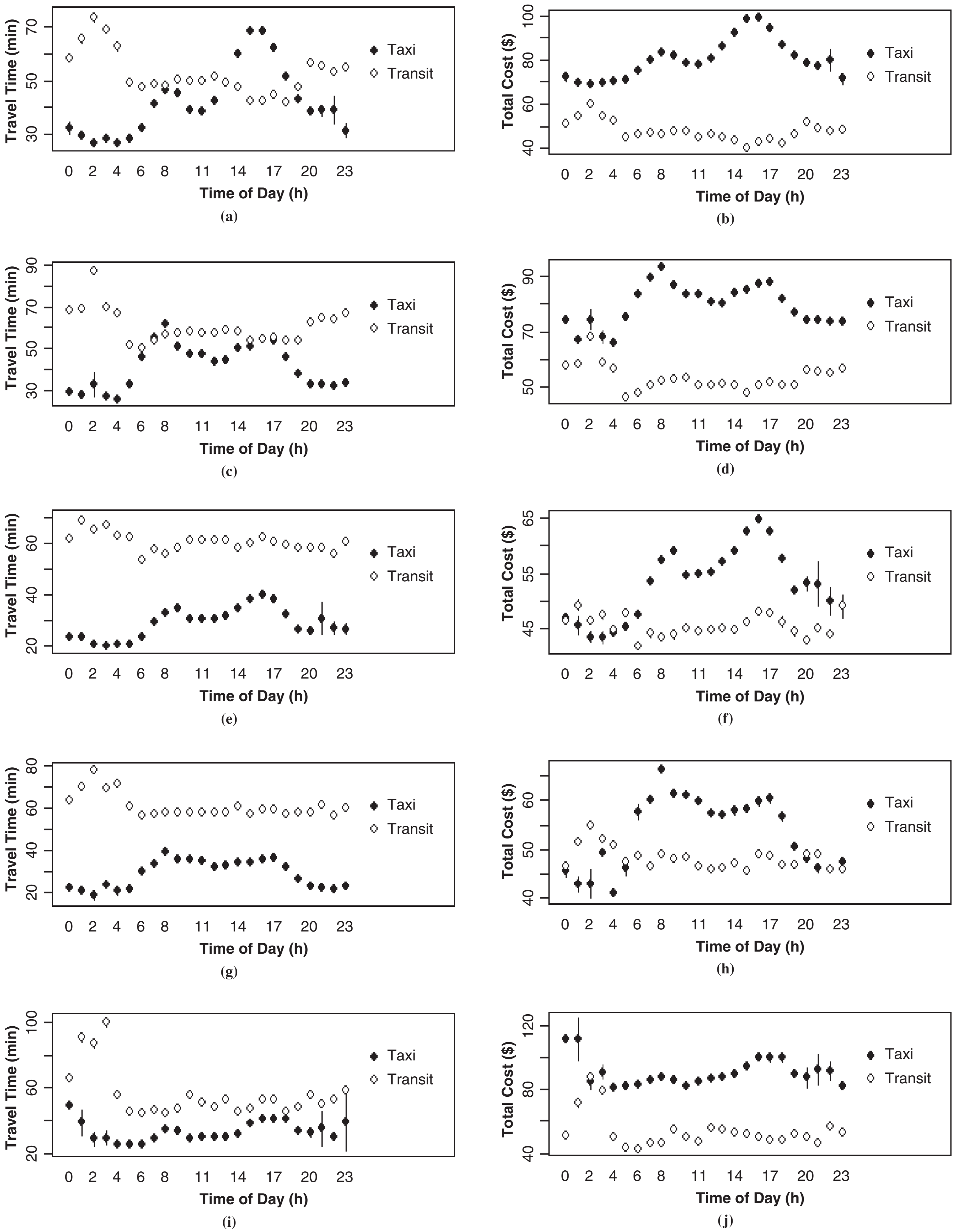

FIGURE 3 Comparisons between mean weekday travel times and total trip costs for taxi and transit with standard errors: (*a*) travel time and (*b*) total costs from Penn Station to JFK Airport, (*c*) travel time and (*d*) total costs from JFK Airport to Penn Station, (*e*) travel time and (*f*) total costs from Penn Station to LGA Airport, (*g*) travel time and (*h*) total costs from LGA Airport to Penn Station, and (*i*) travel time and (*j*) total costs from Penn Station to EWR Airport.

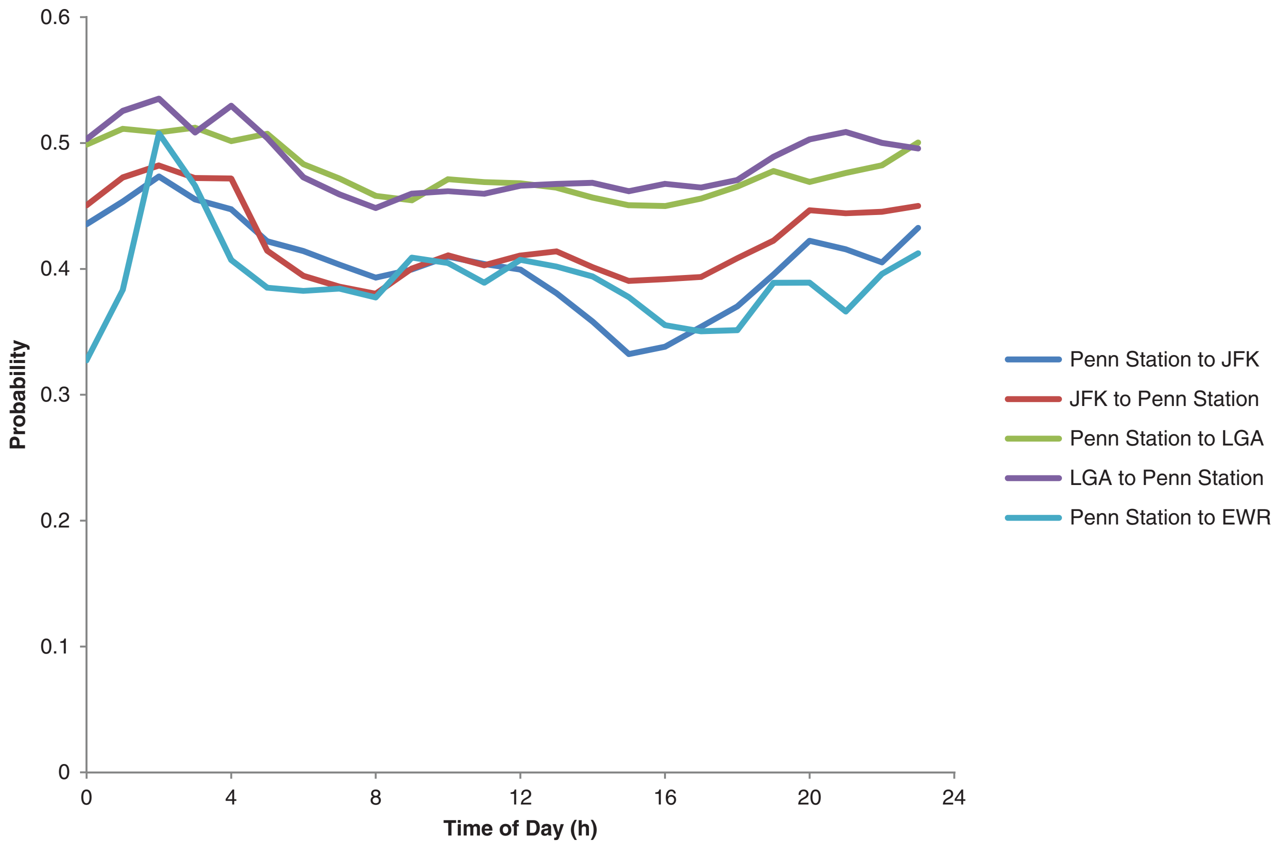

FIGURE 4 Weekday probability of choosing taxi for all airports.

data and the total fare paid, which includes tip. In reality, people may experience an additional penalty for using transit because they need to walk a certain distance to get transit service. These additional benefits or penalties are omitted from the analysis to focus on the effects of money cost and travel time on the competitiveness of each mode.

Sensitivity Analysis

The total cost is also influenced by the value of time and the number of passengers traveling together. Table 1 shows that on average there are 1.6 to 1.8 passengers taking taxis together to go to or from each airport. A sensitivity analysis is performed to investigate the effects of both the value of time and the number of passengers in the group on the probability of an individual's travel mode choice in detail.

The average travel time and fare from all records for taxi and transit are considered as travel time and fare for each O-D pair. The sensitivity analysis considers variation of the value of time, α (in the range of \$10/h to \$70/h), and passenger count, n (in the range of 1 to 3) to see how much influence these factors have on total cost, as shown in Figure 5, *a* to *f*. If the value of time is fixed, changing the number of passengers only affects the taxi fare per person because the transit fare per person is always fixed. The slope in Figure 5 for each mode is the travel time, and the intercept is the fare per person according to Equation 1. Intersections of taxi cost and transit cost are found for all O-D pairs except trips from Penn Station to JFK Airport (Figure 5*a*). The intersection indicates a value of time when the cost of taxi and transit are the same for different numbers of passengers. This value of time at the intersection is a tipping point above which passengers are willing to pay extra fare for the faster mode. For example, the transit cost for trips from JFK Airport to Penn Station intersects with the taxi cost at \$57/h for $n = 2$, indicating that the total cost of taxi is higher when the value of time is less than \$57/h, because the slope for transit exceeds the slope for taxi (Figure 5*b*). This finding means that if two passengers are traveling as a group, it is better to choose transit if the value of time is lower than \$57/h; otherwise it is more cost-effective to choose taxi.

On average, there is no way that a trip from Penn Station to JFK Airport will be less costly by taxi in the assumed range of values of time and number of passengers (Figure 5*a*). For the reverse direction, JFK Airport to Penn Station, taxis do become competitive for sufficiently high values of time and passenger occupancies (Figure 5*b*).

For trips to and from LGA Airport (Figure 5, *c* and *d*), if a passenger is traveling alone, the taxi costs are higher than transit costs when the value of time is less than \$66/h (Penn Station to LGA) or \$61/h (LGA to Penn Station); however, if a passenger is traveling with more than two people, the threshold is \$27/h. This relatively low value is reasonable because there is no direct transit service between Penn Station and LGA Airport. Since the distance is shorter than to any of the other airports, the taxi cost is more competitive.

The trip cost from Penn Station to EWR Airport seems similar to that from JFK Airport to Penn Station, except that the intersection points differ slightly. Transit costs more if the value of time exceeds \$47/h ($n = 2$) or \$17/h ($n = 3$). Considering \$63/h as the value of time for business trips in New York City and \$42/h as the value of time for leisure trips (*5*), it is likely that a business trip will use a taxi for trips from JFK Airport to Penn Station or from Penn Station to EWR

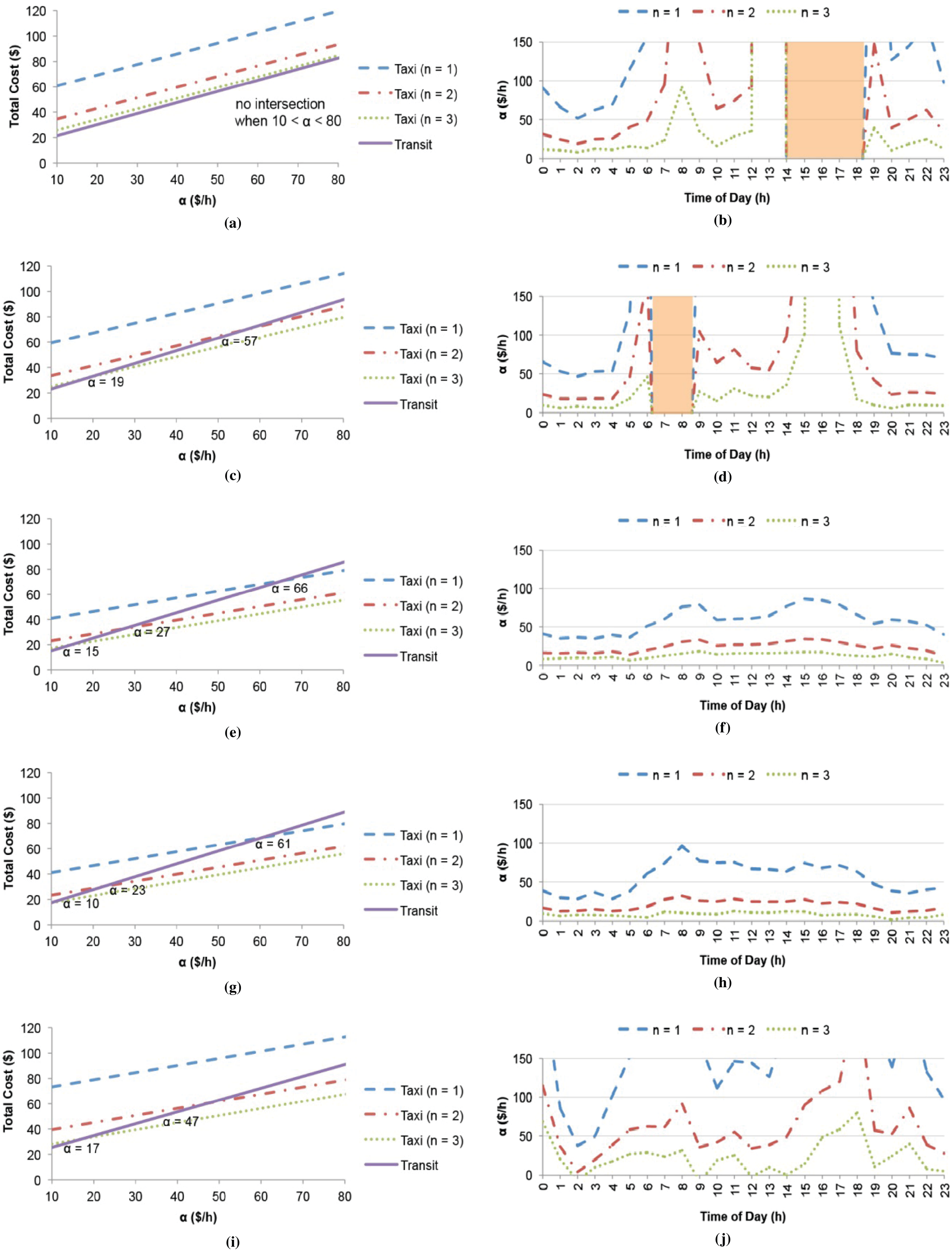

FIGURE 5 Sensitivity analysis on value of time (α) and passenger count (n): cost comparison for (*a*) Penn Station to JFK, (*b*) JFK to Penn Station, (*c*) Penn Station to LGA, (*d*) LGA to Penn Station, and (*e*) Penn Station to EWR; and α-value when mode costs are equal for (*f*) Penn Station to JFK, (*g*) JFK to Penn Station, (*h*) Penn Station to LGA, (*i*) LGA to Penn Station, and (*j*) Penn Station to EWR.

Airport if a passenger is traveling with more than two other people, but a leisure trip will use a taxi only if the passenger is traveling with at least three other people.

To account for the effect on the variation of travel time throughout a day, the threshold value of time within each hour at which passengers will switch their preferred mode is plotted (Figure 5, *f* to *j*). For most cases, travel times are longer by transit than by taxi (i.e., the slope for transit exceeds the slope for taxi), so values of time greater than the threshold are associated with more cost-effective taxi service, and values of time less than the threshold are associated with more cost-effective transit service. For a couple of time periods, transit is actually faster than taxi because traffic congestion has such a severe effect on taxi travel times, and the interpretation switches, so in the shaded areas of Figure 5, *f* and *g,* all trips are more cost-effectively served by transit, regardless of the value of time. During these times, transit is faster and cheaper than taxi.

The relatively low tipping point values at LGA Airport compared with those at EWR and JFK show that taxi is more competitive than transit for that airport, thus appealing to a wider range of values of time. There is also a pattern at all airports that taxi is more competitive in the early hours of the morning (around 2 a.m.) when transit service is also less frequent. These results have policy implications, because they show how airports differ in the competitiveness of ground access modes and how this competitiveness changes by time of day.

Results for EWR Airport (Figure 5*j*) suggest that transit is more competitive from Penn Station to EWR, but for midnight trips taxis have a lower total cost than transit because the frequency of service is lower, and results in longer waiting times. However, because of the relatively long distance between Penn Station and EWR Airport, it is possible that a taxi is more likely to be chosen on the basis of factors such as convenience and comfort, which are not considered in this study.

CONCLUSION

This paper presents a methodology to compare the total cost for two modes of transportation (transit and taxi) by using taxi GPS data and high-resolution transit schedule information. Trips between New York City's Penn Station and three New York area airports (JFK, LGA, and EWR) at different times of day are used to illustrate the methods. As shown in the analysis of total cost and mode choice, transit is found to be more cost-effective than taxi for most times of the day if passengers are traveling alone and value their time at \$40/h, except during some midnight periods when transit service has long headways that contribute a significant amount of time to waiting or transfers.

The sensitivity analysis suggests that people are more likely to choose taxi to travel from Penn Station for airport trips if (*a*) they have a high value of time, (*b*) they are traveling with a large group of people, or (*c*) they are traveling in late-night hours. It was also found that if people are traveling for business trips, taxis become a less costly choice for airport access. For both JFK and EWR Airports, because of the long distance, the taxi fare from Penn Station is very high, thus making transit a more competitive mode most of the time (especially when $n = 1$), even though taxis have an advantage in travel time. However, LGA Airport is closer to Penn Station, and the relatively low taxi fare and low travel time make the taxi a more competitive choice for that O-D pair.

The results show that the total cost or travel time for taxis always has a morning peak (between 6 and 10 a.m.) and an afternoon peak (between 1 and 6 p.m.). The taxi data provide an indication of traffic conditions in New York City (*18*), so the use of these data to calculate the travel cost could incorporate both the temporal and spatial effects of traffic congestion in the city. However, this study is limited to the temporal analysis of the five most popular O-D pairs for the airports, which all include trips to and from Penn Station. This can create bias if used to estimate total costs for the entire city. Future applications could be expanded to consider the spatial dimension as well by including multiple O-D pairs distributed all over the city.

There are other factors that affect the choice of mode for trips to and from the airport, such as convenience and comfort, which are not considered in this study because they cannot be easily measured and quantified. With additional data about the number of passengers using each mode by time of day, it may be possible to gain some insights into the effect of these less tangible factors by comparing the expected mode shares from the utility functions in this paper with the observed mode shares.

This paper could be used as an example of a practical method to estimate the travel cost including both time and money. As information and resources such as travel time and fare are increasingly accessible, it is possible to design a smartphone app or a small computer program at the transit ticket vending machine to estimate total cost using this methodology. This information along with the choice model can be used to understand the factors that affect the aggregate mode choice decisions of the public. This information will be useful for transportation planners and policy makers to improve the quality of travel options available to people traveling to and from airports.

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