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Substitution of Ride-Hailing Services for More Sustainable Travel Options in the Greater Boston Region

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Abstract

The recent and dramatic growth in ride-hailing activity is a bellwether of a coming transportation revolution driven by on-demand services. The impacts of ride-hailing services on the transportation system have been immediate and major. Yet, public agencies are only beginning to understand their magnitude because the private ride-hailing industry has provided limited amounts of meaningful data. Consequently, public agencies responsible for managing congestion and providing transit services are unable to clearly determine who uses ride-hailing services and how their adoption influences established travel modes, or forecast the potential growth of this emergent mode in the future. To address these pressing questions, an intercept survey of ride-hailing passengers was conducted in the Greater Boston region in fall 2017. Ten ride-hailing drivers, recruited and trained by the authors, asked passengers to complete surveys during their ride-hailing trip. The tablet-based survey instrument recorded nearly 1,000 passenger responses with regard to socioeconomic background, mobility options, and trip context. These responses, which enabled a robust description of ride-hailing passengers for the region, were used to analyze how new on-demand mobility services such as Uber and Lyft may be substituting travel by other modes. The study substantiates previous findings and advances knowledge of who is utilizing this new mobility option and what factors influence its adoption over public and active transportation modes. The results are intended to inform public policies ensuring that shared mobility technologies will complement existing multimodal landscapes and not worsen existing environmental concerns or equity gaps related to individual mobility.

In the past decade, ride-hailing services have dramatically altered the way that residents, employees, and visitors travel. Although the impacts of ride-hailing services on the transportation system have been major, public agencies are only now beginning to understand their magnitude because meaningful data have not been readily provided by this private industry. In Massachusetts, where Uber started service in 2011 and Lyft started two years later (*1*), 64.8 million ride-hailing trips were taken in 2017, with over 59.9 million of these trips originating in the Greater Boston region (*2*),accounting for an estimated 1.3% of all trips (*3*). While informative, aggregate figures are of limited utility to legislators and agencies looking for evidence-based policies to effectively manage new mobility industries and technologies that affect transportation systems, public health, greenhouse gas emissions, and other immediate issues of concern. At present, public agencies responsible for managing congestion and providing transit services are unable to describe clearly who uses ride-hailing services and how the adoption of this innovative mobility option influences more sustainable travel modes; nor are they able to forecast how increased availability and acceptance of ride-hailing may affect travel demand and congestion in the future.

The appeal of a fast, flexible, and convenient mobility option with a potential to reduce auto ownership, which is offered by these services, has fostered a direct competition with more sustainable modes, including public transit, cycling, and walking (*4*). In the United States, ride-hailing and taxi services may likely exceed local bus ridership by the end of 2018 (*5*). This is a staggering statistic when one considers that the ride-hailing industry is in direct competition for passengers with the traditional taxi industry, which is clearly vulnerable to the popularity of app-based, on-demand ride-hailing services (*6*). However, to date, only a handful of studies has investigated the substitution effects related to rapid ride-hailing

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adoption despite a clear policy-related need for more independent data sources describing ride-hailing passengers and their travel behaviors (*4*). Transportation policy tools, including travel demand models, rely in many cases on surveys that predate the emergence of ride-hailing services and, therefore, are hindered in their ability to adequately forecast the impact of these new mobility options until an evidence base has been established.

Study Objectives

The objectives of this study are twofold. First, after designing and directing an in-vehicle intercept survey of ride-hailing passengers, the aim is to introduce a profile of ride-hailing passengers in the Greater Boston region. Second, building on this primary data collection effort, the aim is to identify a set of factors predicting the substitution of ride-hailing services for more sustainable travel options. In achieving these objectives, our study seeks to bolster the evidence base on ride-hailing research that is required to better inform regional travel demand models and forecasting methods, understand the impacts of this emergent mobility option on the transportation system, and ultimately improve transportation planning and operations.

Literature Review

In an early study of ride-hailing activity, Rayle et al administered an intercept survey of 381 ride-hailing passengers in three San Francisco neighborhoods to gain insight into who is adopting these services and how those choices are affecting established travel modes (*4*). When compared with San Francisco's population, surveyed ride-hailing passengers were more likely to be under 35 years old, have a higher level of educational attainment, and reside in a higher-income household. In terms of mode substitution, 10% of surveyed ride-hailing passengers would have walked or cycled if a ride-hailing service were not available, with another 33% of respondents stating they would have used bus or rail services. In sum, Rayle et al (*4*) concluded that 43% of surveyed ride-hailing trips created new vehicle trips.

Operating as a ride-hailing driver, Henao conducted an onboard intercept survey of 311 passengers in Denver (*7*). Similar to Rayle et al's study, surveyed ride-hailing passengers tended to be younger, more educated, and have a higher household income when compared with the citywide population. Examining sustainable mode substitution patterns, 22% and 12% of passengers stated they would have traveled via public transit or active transportation modes, respectively, if a ride-hailing service was not available for their surveyed trip. An additional 12% of respondents reported they would not have traveled if it was not for the access to this new mobility service, underscoring the potential for ride-hailing services to unlock a latent demand for auto-related travel.

Clewlow and Mishra investigated the results of an online transportation survey conducted in seven metropolitan regions, including Boston, which echoed the prior observations that ride-hailing adopters tend to be younger, more educated, and wealthier than the general population (*8*). By inquiring of ride-hailing passengers as to which transportation alternatives were most commonly replaced in trips made by Uber and Lyft, they discovered that 15% of passengers would have otherwise traveled by rail, 24% would have walked or cycled, and another 22% would have conducted less travel. In a separate multiregional survey of shared mobility users, Feigon and Murphy found that 15% of respondents whose most frequent shared mobility service was ride-hailing would have used bus or rail if this new travel option was unavailable, with another 17% of ride-hailing passengers stating they would have walked or cycled (*9*). Using online survey data collected exclusively within California, Alemi et al examined differences in substitution patterns between respondents who reported adopting ride-hailing services at least once per month and those who did not (*10*). The monthly ride-hailing service adoption group was shown to more often substitute these new mobility services for both active and public transportation modes than the group who seldom adopted ride-hailing services. Study findings posit that if ride-hailing service adoption continues to escalate, travel by more sustainable alternatives may experience decreased mode shares.

In summary, the current knowledge on ride-hailing activity, although sparse, suggests that these services are popular among younger and more educated individuals who are shifting their travel toward auto-based modes and generating previously unrealized vehicle trips. Most research has analyzed data from ride-hailing passengers surveyed outside their trip context, limiting the ability to study trip-level attributes describing mode substitution patterns. In short, more evidence is needed to assess whether the rapid adoption of ride-hailing services is supporting or obstructing planning goals of improved mobility and environmental sustainability (*11*).

Methods

Survey Design

An electronic survey instrument was developed to learn more about ride-hailing passengers in the Greater Boston region. This original survey instrument contained a set of 18 questions prompting participants to provide information on their sociodemographic and economic background and transportation options, as well as characteristics and motivating factors of their recorded ride-hailing trip, and proclivity toward adopting this emergent mobility option. English- and Spanish-language versions of the instrument were produced.

To provide a regional profile of ride-hailing passengers, the questionnaire was designed to elicit responses about the ride-hailing passenger's age, gender, educational attainment, work status, and race and ethnicity, in addition to his or her household's annual income and composition. Questions related to household car ownership and personal travel alternatives were included to help define a passenger's available mobility options. Participants were also asked to report the postal code of their residence.

The survey instrument sought to recognize the context of the observed ride-hailing passenger's trip. Survey participants were asked to identify the ride-hailing service used for their trip (e.g. Lyft, Uber), size of their party, estimated ride cost, and primary activity at their trip origin and destination. Of particular interest to this study, the questionnaire asked individuals how they would have traveled if a ride-hailing service was not available for their trip and what reasons motivated their decision to adopt a ride-hailing service. For the mode substitution question, participants were only able to select one alternative travel mode. A final ride-hailing-related question asked how often the passenger had utilized this new mobility option over the past 3 months: first ride, rarely (less than once per month); sometimes (—one to three times per month); regularly (—one to three times per week); or frequently (more than four times per week).

Survey Administration

An in-vehicle intercept survey of ride-hailing passengers in the Greater Boston region was conducted during a 4-week period in October and November 2017. The survey instrument was administered by 10 ride-hailing drivers who were equipped with a portable tablet device with a pre-installed version of the survey instrument. Two ride-hailing drivers were recruited based on participation in an agency-led focus group aimed at understanding the traffic and travel impacts of regional ride-hailing activity from a driver's perspective. Two additional drivers were recruited by a ride-hailing driver assistance company who sent a message to Boston area drivers about participating in a study about travel choices. The remaining six drivers were recruited after responding to a separate posting placed on two ride-hailing user groups hosted on a social media website. The 10 drivers, who represented a spectrum of four ride-hailing companies and resided in seven municipalities, were trained by the authors on survey content and administration.

Ride-hailing drivers were instructed to ask boarding passengers about participation in a short survey to learn about regional transportation options. Placed inside each vehicle, two placards also described the survey participation opportunity. Drivers received a monetary incentive for participation in the study and an additional incentive for each collected passenger survey. Passenger survey respondents were invited to enter their contact information for a chance to win a gift card to an electronic commerce company. A further description of the survey design and administration is detailed in Gehrke et al (*12*).

Analytic Design

To address the primary study objectives, passenger survey results were summarized and then examined in a two-part analysis of what factors predict the substitution of ride-hailing services for more sustainable modes. By synthesizing the survey results, a profile of ride-hailing passengers in the Greater Boston region was produced as well as a comparison point to existing studies conducted in other major metropolitan regions. To assess the representativeness of the collected sample to the socioeconomic composition of residents in the 101 municipalities in the Greater Boston region, survey results were compared with age, income, and race and ethnicity data provided by the 2012–16 American Community Survey 5-year estimates.

Building on this descriptive summary, a subsequent analysis was performed to identify the various factors associated with a surveyed passenger's decision to substitute a ride-hailing service for public transit use and active transportation modes. Separate binary logistic regression models were estimated to determine the set of individual-level socioeconomic features, mobility options, and trip characteristics that predicted the choice to replace either public transit (model 1) or active transportation (model 2) trips. Specification of these two substitution models was iteratively performed by identifying significant predictors within each variable category and applying a backward elimination process to a full model of pooled socioeconomic, mobility, and trip attributes.

Other factors, including measures of the environmental context found at either trip end, are hypothesized to affect the decision to substitute ride-hailing service adoption for a more sustainable transportation option (public transit or walk/bike) rather than another vehicle-based mode (private car, taxi). While detailed spatial data were not passively collected for the intercepted ride-hailing trips, passengers provided postal codes associated with their residence and information on the primary activity conducted at the trip origin. As a result, the effect of the residential built environment and socioeconomic,

Table 1. Descriptive Statistics of Ride-Hailing Passenger Survey Respondents (n = 944)

Variable	n (%)	$\bar{x}$	Variable	n (%)	$\bar{x}$
Socioeconomic features			*Trip characteristics*		
Individual age			Mode substitution		
18–21 years	163 (17)	NA	Public transit	389 (41)	NA
22–34 years	603 (64)	NA	Active transport	112 (12)	NA
35–44 years	96 (10)	NA	Vehicle	376 (40)	NA
45 years or older	71 (8)	NA	No travel	46 (5)	NA
Individual education			Service type		
High school or less	121 (13)	NA	Standard	752 (80)	NA
Undergraduate college	153 (16)	NA	Pooled	190 (20)	NA
Advanced degree	234 (25)	NA	Party size	—	1.52
Individual race/ethnicity			Trip cost		
Asian	110 (12)	NA	Less than $10	336 (36)	NA
Black/African American	61 (6)	NA	$10–$20	402 (43)	NA
Hispanic/Latino	86 (9)	NA	Greater than $20	192 (20)	NA
White	579 (61)	NA	Monthly frequency		
Two or more races	26 (3)	NA	First ride	12 (1)	NA
Individual gender			Rarely	39 (4)	NA
Female	498 (54)	NA	Sometimes	268 (28)	NA
Male	432 (46)	NA	Regularly	347 (37)	NA
Household income			Frequently	267 (28)	NA
Less than $38,000	200 (21)	NA	Day of week		
$38,000–$60,000	170 (18)	NA	Weekend	329 (35)	NA
$60,001–$82,000	125 (13)	NA	Time of day		
$82,001–$110,000	91 (10)	NA	Morning peak	155 (16)	NA
$110,001–$137,000	54 (6)	NA	Midday	140 (15)	NA
Greater than $137,000	134 (14)	NA	Evening peak	171 (18)	NA
Household children			Night	478 (51)	NA
None	799 (85)	NA	Trip purpose		
One or more	128 (14)	NA	Home-based	275 (29)	NA
Mobility options			Non-home-based	589 (62)	NA
Household cars	—	1.04	Reason for use		
Private car	422 (45)	NA	Multitasking ability	85 (9)	NA
Driver's license	705 (75)	NA	Cannot drive	114 (12)	NA
Carshare membership	100 (11)	NA	Car unavailable	326 (35)	NA
Public transit pass	330 (35)	NA	Parking is difficult	217 (23)	NA
Personal bike	214 (23)	NA	Transit unavailable	163 (17)	NA
Bikeshare membership	32 (3)	NA	Quicker than transit	561 (59)	NA
Parking at residence	266 (28)	NA	Weather	175 (19)	NA

Note: NA = not applicable.

mobility, and trip-level factors on mode substitution were assessed for home-based ride-hailing activity. Built environment variables describing the density of residents and employees, diversity of land uses, and design of the street network were tested (*13*), along with a zonal binary metric noting the presence of a rapid transit station in this multinomial logistic regression model of mode substitution. For this third model, which applied a specification process similar to the development of the prior two models, the reference case was the substitution of a ride-hailing service for vehicle-based travel compared with the alternatives of replacing public transit use, active travel, or no travel. The substitution of ride-hailing services for one of these three alternatives represents the addition of a new vehicle to the transportation network.

Results

Profile of Ride-Hailing Passengers

In total, 944 ride-hailing passengers provided valid responses during the 4-week data collection period. Table 1 summarizes the socioeconomic features and mobility options of the intercept survey respondents in addition to several characteristics associated with their observed ride-hailing trip. Figure 1 provides an overview of the residential locations of these passengers, with the caveat that 31% of intercepted ride-hailing trips did not start or end at an individual's home location.

An overwhelming majority of survey respondents (766 passengers, 82% of the sample) were born after 1983. Nearly two-thirds (603 passengers, 64% of the sample)

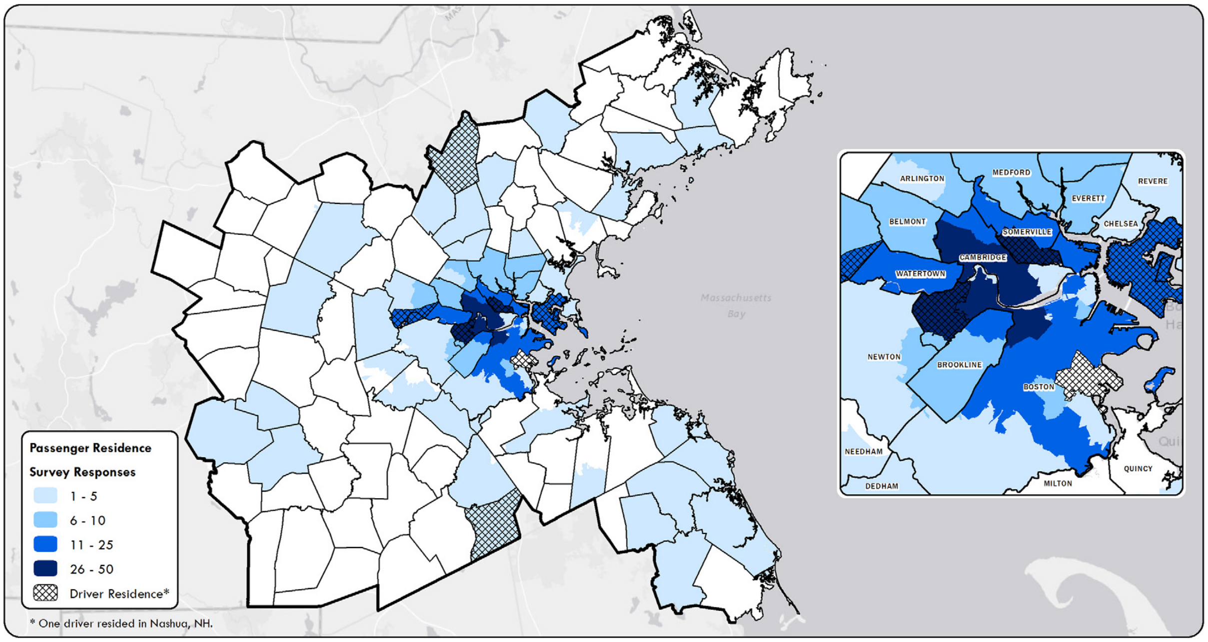

Figure 1. Residential location of ride-hailing passenger survey respondents in the Greater Boston region.

of respondents were between 22 and 34 years old; this age cohort only constitutes about one-quarter (23%) of the residential population in the Greater Boston region. In contrast, residents who are 65 years of age or older comprise 16% of the regional populace, but represented less than 1% of the survey sample. In fact, only 8% of surveyed passengers reported being 45 years or older.

In terms of race and ethnicity, after excluding the 9% of passengers who did not respond to this question, 67% of passengers identified as White and non-Hispanic or non-Latino, which is 5% lower than the regional share. Of the completed responses, roughly 10% of ride-hailing passengers identified as Hispanic or Latino, whereas 13% were of Asian descent and 7% identified as Black or African American. In the Greater Boston region, 9% of the residential population is Black or African American, with 8% of Asian descent.

Over four-fifths (82%) of surveyed passengers also provided an estimated annual household income. Of these respondents, over one-quarter (26%) reported annual household earnings below $38,000, which is comparable to the regional share of households with an income less than $40,000 (28%). Among surveyed ride-hailing passengers in this lowest income cohort, 57% reported having either part- or full-time employment, whereas 41% were students presently unemployed. Approximately 17% of willing respondents reported an annual household income in the highest bracket, which is a lower share than the 23% for the region.

Examining auto-related mobility options, the average number of household cars per surveyed ride-hailing passenger was about one, with 45% of respondents having access to a private car and 11% possessing a carshare membership. Only 28% of passengers noted having vehicle parking at their residence. Over one-third (35%) of respondents had a weekly or monthly public transit pass, whereas under one-quarter (23%) of ride-hailing passengers owned a personal bike and 3% had a bikeshare membership.

Turning to ride-hailing travel characteristics, one-fifth (20%) of surveyed trips used a pooled service such as Lyft Line or uberPOOL, whereas the average party size for a trip was 1.52 passengers. After excluding non-responses, most trips cost less than $20 (79%) and originated somewhere other than the survey respondent's home (68%). Nearly two-thirds (65%) of intercepted trips occurred on a weekday, with about half of these trips (51%) occurring between 7:00 p.m. and 6:00 a.m. and another third (34%) occurring during either the morning (6:00–9:00 a.m.) or evening (4:00–7:00 p.m.) peak travel periods.

For the recorded trip, of the 923 ride-hailing passengers who answered the direct question about mode substitution, 59% of ride-hailing trips added a new vehicle to the road. The most common reasons why a ride-hailing service was adopted for the recorded trip were that this mobility option was considered quicker than public transportation (59%); the passengers did not have

Table 2. Factors Predicting Trip-Level Substitution of Ride-Hailing Services for Public Transit Modes

Variable	Estimate (β)	Standard error	*p*-value
Socioeconomic features			
Household income: $38,000–$60,000	−0.37	0.24	0.11
Household income: $60,001–$82,000	−0.34	0.26	0.18
Household income: $82,001–$110,000	−0.46	0.28	0.10
Household income: $110,001–$137,000	−1.51	0.39	0.01
Household income: greater than $137,000	−1.06	0.26	0.01
Mobility options			
Public transit pass	1.11	0.17	0.01
Trip characteristics			
Trip cost: less than $10	0.02	0.19	0.90
Trip cost: greater than $20	−0.62	0.23	0.01
Day of week: weekend	−0.43	0.17	0.01
Reason for use: transit unavailable	−0.78	0.22	0.01
Reason for use: quicker than transit	0.88	0.17	0.01
Reason for use: weather	0.44	0.21	0.04

Note: Log-likelihood = −442.68; *n* = 758.

access to a vehicle (35%); and parking was either too difficult or expensive (23%). About two-thirds (66%) of ride-hailing passengers who provided responses stated that they had used these services on a weekly basis over the past 3 months.

Substitution of Ride-Hailing Services for Sustainable Travel Options

The disparate factors predicting a ride-hailing passenger's self-reported likelihood to substitute public transit or active travel are shown in Table 2 and Table 3, respectively. Investigating the replacement of public transit over other alternatives for the intercepted ride-hailing trip, passengers with higher annual household incomes were less likely to have replaced public transit use (bus or rail) than individuals within the lowest income bracket. Additionally, passengers who possess a weekly or monthly transit pass were more likely to have substituted ride-hailing services for public transit use than those without a subsidized pass, which further underscores an anticipated ridership competition between the two modes. Looking at trip-level predictors of mode substitution, ride-hailing trips of a greater cost were less likely to have replaced public transit use than other mobility options such as a private vehicle or taxi, when compared with trips costing between $10 and $20. A self-perceived quickness of ride-hailing versus public transit for the surveyed trip as well as poor weather conditions were also predictive of substitution for public transit, as was the reported unavailability of public transit.

A ride-hailing passenger's mobility options and specific trip attributes were more likely to have predicted the substitution of ride-hailing services for active travel (bike or walk) than individual- or household-level socioeconomic characteristics. Possession of a transit pass had a negative effect on substitution for active travel modes, whereas ownership of a personal bike significantly predicted the adoption of ride-hailing for active travel. Similar to the substitution for public transit model in which individuals with a subsidized pass chose to adopt ride-hailing services, this finding highlights that individuals with direct access to a bike may still forego the fareless travel option. Ride-hailing trips of shorter distances, reflected by lower trip costs, were more likely to have replaced biking and walking trips, as were intercepted ride-hailing trips that occurred during the evening peak period when compared with the morning peak. Finally, poor weather conditions, which predicted the substitution of ride-hailing for public transit, also factored in the substitution of ride-hailing services for active travel modes. Expectedly, given the extended exposure that pedestrians and cyclists have to inclement weather along their travel route compared with public transit passengers accessing a bus stop or rail station, the effect size for this ride-hailing adoption reason was greater in the substitution for active travel model.

Examining the substitution patterns of home-based ride-hailing activity (Table 4), transit pass possession predicted the substitution of ride-hailing for public transit and generation of latent travel rather than vehicle (private or taxi) use. Likewise, when compared with ride-hailing passengers who reported replacing a vehicle trip, passengers using a pooled (shared ride) service were more likely to have substituted ride-hailing for transit use or produced trips that would have otherwise not been conducted. While generating new vehicle trips via ride-hailing adoption, these trips were more likely to have been higher occupant, shared rides. On average,

Table 3. Factors Predicting Trip-Level Substitution of Ride-Hailing Services for Active Transport Modes

Variable	Estimate (β)	Standard error	*p*-value
Mobility options			
Public transit pass	−0.61	0.25	0.01
Personal bike	0.54	0.25	0.03
Trip characteristics			
Trip cost: less than $10	1.51	0.26	0.01
Trip cost: greater than $20	−0.87	0.51	0.09
Time of day: midday	0.74	0.18	0.12
Time of day: evening peak	1.07	0.44	0.02
Time of day: night	0.64	0.41	0.12
Reason for use: weather	1.20	0.23	0.01

Note: Log-likelihood = −274.04; n = 911.

Table 4. Factors Predicting Substitution of Ride-Hailing Services During Home-Based Ride-Hailing Trips

Substituted mode (referent = vehicle)	Active transport	No travel	Public transit
Variable	β (SE)	β (SE)	β (SE)
Mobility options			
Household cars	0.25 (0.34)	0.49 (0.46)	−0.77 (0.26)*
Public transit pass	−0.26 (0.67)	1.92 (0.83)*	1.62 (0.44)*
Trip characteristics			
Service type: pooled	0.83 (0.76)	2.18 (1.07)*	1.38 (0.63)*
Trip cost: less than $10	1.51 (0.65)*	−1.57 (1.09)	−0.29 (0.49)
Trip cost: greater than $20	−16.19 (1,962.41)	−1.28 (1.03)	−1.34 (0.53)*
Reason for use: parking is difficult	−1.51 (0.78)	−2.58 (1.23)*	−0.56 (0.45)
Reason for use: transit unavailable	−1.18 (1.10)	0.27 (0.99)	−1.17 (0.59)*
Reason for use: weather	2.34 (0.93)*	1.21 (1.27)	1.45 (0.77)
Built environment			
Connected node ratio	19.16 (11.38)	−5.60 (13.17)	33.05 (8.57)*
Employment–population ratio	1.00 (0.38)*	1.11 (0.39)*	0.89 (0.37)*
Gamma index	−12.96 (8.81)	−9.00 (11.37)	−25.72 (7.32)*
Rapid transit station	3.23 (1.31)*	−0.76 (0.98)	1.20 (0.58)*

Note: Log-likelihood = −169.42; McFadden R^2 = 0.35; Likelihood ratio test (χ^2) = 180.92 ($p < 0.01$).
*$p < 0.05$.

public transit was more likely to be unavailable (β = −1.17, $p < 0.05$) for would-be public transit users than those who substituted ride-hailing for the use of another vehicle, whereas expensive or difficult parking conditions (β = -2.58, $p < 0.05$) predicted a latent demand for ride-hailing travel when the alternative option would have been a vehicle. Similar to results in the prior substitution models, less expensive and presumably shorter ride-hailing trips were more likely to have replaced bike and walking than trips taken with a vehicle, whereas more expensive and likely longer ride-hailing trips were less likely to have replaced public transit adoption than vehicle use.

Analyzing the effect of residential environment context on substitution patterns, the proximity to a nearby rapid transit station predicted the substitution of ride-hailing services for walking, biking, and public transit rather than substitution for another vehicle. Although substitution is contingent on mode availability, residing in a transit-accessible neighborhood often entails better multimodal options that are in this case being rejected for travel in a ride-hailing vehicle. Residing in an area with a high employment–population ratio was more likely to predict the substitution of ride-hailing services for walking, biking, transit, or no travel at all than the substitution of ride-hailing for vehicle travel. Residents of environments with a gridded street network, as described by a high connected node ratio and low gamma index, were more likely to substitute ride-hailing services for transit than they were to substitute ride-hailing for travel in another auto vehicle.

Discussion

The policy implications of this research are immediate. Foremost, the design and administration of a novel onboard survey instrument permitted the collection and analysis of ride-hailing data on passengers and their specific trip context that raise as many questions as they answer. State legislature and agencies must press for more disaggregate data reporting from the private ride-hailing industry, whose business model and competitive marketplace largely discourage the sharing of detailed data with public agencies. Recent laws and regulations in Massachusetts have delivered to the public a first-in-the-nation statewide picture of ride-hailing activity, which provides novel insight into the magnitude of which new on-demand mobility services are transforming the transportation system (*3*). Unfortunately, these data are summarized by municipality and, thus, limited in their inability to guide traffic management and operations strategies. Opportunities to mandate the provision of additional public data reports, which protect driver and passenger privacy, should be sought after to not only understand ride-hailing passenger activity and behaviors, but also offer the insight required to understand the possible travel patterns of an automated vehicle fleet.

The substitution of ride-hailing services for travel via public transit, walking, and cycling has revealed myriad economic, environmental, and social impacts related to increased ride-hailing adoption. A shifting of trips away from public transit toward ride-hailing services will result in a decline in transit ridership and subsequently a drop in revenue, potentially initiating a negative spiral of higher per-trip subsidies, service cuts, and a greater shift of commuters to ride-hailing services. Presently, ride-hailing companies operating in Massachusetts pay a 20-cent assessment per trip, of which 5 cents goes to the Commonwealth Transportation Fund and another 10 cents to the municipality of the trip's origin for addressing the transportation impact of ride-hailing services (the remaining 5 cents is directed to the repositioning and retraining of taxi industry employees). An increase to this legislatively-mandated ride assessment may help public transit agencies to effectively plan and invest in complementary services. Although our study reveals that ride-hailing companies compete with public transit agencies for passengers, opportunities exist for these services to encourage complementary usage (i.e. first-mile/last-mile service planning) and promote multimodal lifestyles (*14*).

Whereas our study found that 59% of surveyed ride-hailing trips added a new vehicle on the road, past studies have noted that policy makers should be cautiously optimistic in the prospect for ride-hailing services to reduce vehicle use and ownership as ride-hailing adoption continues to accelerate (*4*, *8*). Yet, in our survey, only 20% of ride-hailing passengers noted they were using a pooled service, with 58% of passengers who selected the alternative standard service traveling alone, despite the reduced costs associated with pooled or shared rides. Furthermore, of the trips where ride-hailing substituted the use of another vehicle in our study, only 16% of this subset of surveyed passengers stated they would have driven alone. Accordingly, public policies prioritizing roadway space to high-occupancy vehicles (e.g. pooled or ride-sharing trips) and designating curb-side space for ride-hailing passenger pick-up/drop-off in high-activity locations are paramount to countering environmental concerns of increased greenhouse gas emissions from heightened ride-hailing vehicle adoption.

Finally, although technological efficiencies enable ride-hailing services to provide improved mobility, further knowledge is needed to determine if this new travel option is exacerbating or improving existing racial and economic inequities. Our study, which did not explicitly explore this important issue, found that the race or ethnicity of a surveyed ride-hailing passenger had no significant effect on travel mode substitution patterns. However, surveyed passengers with a higher household income were less likely than other passengers to substitute ride-hailing for public transit services. Although inconclusive, a significant finding that suggests individuals of lesser financial means may be more inclined to choose the more costly shared mobility option. As such, policies that motivate a restructuring of ride-hailing fees to lessen the economic burden of lower-income and minority individuals who may have limited access to a private vehicle or high-quality transit services should be introduced.

Conclusion

This study provides a new data source on ride-hailing activity collected in a trip context, with findings that substantiate and advance the insufficient knowledge of who is utilizing this new mobility option and what factors are most salient in understanding its adoption over more sustainable travel alternatives. In creating a profile of ride-hailing passengers in the Greater Boston region, we found that adopters of these services tended to be relatively younger and more educated than the regional population. Contrasting with previous studies, our sample of respondents represented a more balanced income distribution, with more individuals reporting lower household earnings. In terms of mode substitution patterns, we found that ride-hailing passengers with a greater household income were less likely to replace transit use than individuals with less financial means. As expected, trip-level attributes, which have not been modeled in prior studies, had a substantial effect on the substitution of ride-hailing services for more sustainable options. Our study also found that residents of compact neighborhoods with public transit access were more likely to generate new car trips, as their trips would otherwise have been taken by public transit or active transportation.

While new and informative, this study and its findings have several limitations. First, data collected from an intercept survey instrument with a monetary incentive for participation are unlikely to produce a truly representative sample of the ride-hailing market. Our survey was administered by 10 drivers from distinct parts of the region with different work strategies, but our sampling design was not targeted and the resulting sample is therefore convenient. Second, the ride-hailing profiles and substitution patterns found in this study are specific to the Greater Boston region, therefore our findings may be context-specific and not entirely comparable to trends in other regions. Third, our study would have benefited from the availability of passively-collected, spatially-explicit travel information on the route and trip ends. As a result, built environment features, which likely affect ride-hailing activity across trip purposes, were only evaluated for home-based travel because of the absence of locational data beyond the self-reported home postal code. Finally, a distinction between rail and bus in the survey question related to mode substitution would have allowed for a more robust and nuanced analysis of substitution for public transit predictors. Yet, despite these and other shortcomings, our study offers valuable insight into the market segments who are adopting ride-hailing services and how ride-hailing services' rise in popularity may be producing less sustainable travel behaviors.

Author Contributions

The authors confirm contribution to the paper as follows: study conception and design: S. R. Gehrke, A. Felix, T. G. Reardon; data collection: A. Felix; analysis and interpretation of results: S. R. Gehrke, T. G. Reardon; draft manuscript preparation: S. R. Gehrke. All authors reviewed the results and approved the final version of the manuscript.

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