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Testing Curbside Management Strategies to Mitigate the Impacts of Ridesourcing Services on Traffic

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Abstract

Increased use of ridesourcing leads to increased pick-up and drop-off activity. This may slow traffic or cause delays as vehicles increase curb use, conduct pick-up and drop-off activity directly in the travel lane, or slow to find and connect with passengers. How should cities respond to this change in an effort to keep travel lanes operating smoothly and efficiently? This research evaluates two strategies in Seattle, WA, in an area where large numbers of workers commute using ridesourcing services: (i) a change of curb allocation from paid parking to passenger load zone (PLZ), and (ii) a geofencing approach by transportation network companies (TNCs) which directs their drivers and passengers to designated pick-up and drop-off locations on a block. An array of data on street and curb activity along three study blockfaces was collected, using video and sensor technology as well as in-person observations. Data were collected in three phases: (i) the baseline, (ii) after the new PLZs were added, expanding total PLZ curb length from 20 ft to 274 ft, and (iii) after geofencing was added to the expanded PLZs. The added PLZs were open to any passenger vehicle (not just TNC vehicles), weekdays 7:00–10:00 a.m. and 2:00–7:00 p.m. The results showed that the increased PLZ allocation and geofencing strategy reduced the number of pick-ups/drop-offs in the travel lane, reduced dwell times, increased curb use compliance, and increased TNC passenger satisfaction. The two strategies, however, had no observable effect on travel speeds or traffic safety in the selected study area.

In recent years, many U.S. cities have seen a rapid increase in ridesourcing trips by transportation network companies (TNCs), such as Uber and Lyft. By providing application dispatch services, TNCs allow travelers to connect with drivers via smartphone apps. The share of Americans who have used TNC services has more than doubled since 2015, growing from 15% to 36% (*1*). Goldman Sachs reported an estimate of 15 million trips a day served by TNC services globally, and expects that number to grow by more than five times by 2030 (*2*).

The increase in ridesourcing use and consequently in pick-up/drop-off activity has dramatically increased demand for curbside passenger loading zones (PLZs) in certain areas. Frequent passenger pick-up and drop-off can cause safety hazards and congestion, affect public transit operations, and block pedestrian, bike, and Americans with Disabilities Act (ADA) access (i.e., ramps and curbs) (*3*). Unless dedicated spaces are reserved for pick-up/drop-off activity, TNC vehicles stop and wait at spaces allocated for other purposes or in the travel lane itself, potentially blocking or slowing traffic and adding to congestion. This behavior has been reported in several studies that have assessed the effects of on-street parking on traffic congestion (*4*–*6*), and in those that looked into the impacts of TNCs on traffic congestion and concluded that they add to vehicle-miles traveled and congestion (*7*–*10*).

In urban areas, the demand for pick-up/drop-off curbside access competes with a large variety of other uses, such as vehicle parking, bike lanes, and commercial loading. As a result, curbsides have become especially congested and hotly contested in vibrant areas near central business districts, bars, restaurants, clubs, sports venues, or along other high-demand corridors. This poses challenges for planners and policy makers as how best to manage curb space in response to rapidly growing new mobility services and in the context of their broader transportation initiatives and goals. The pressure can be

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better understood by pointing out that in a 2012 review of national curbside management practices, there was no mention of taking passenger pick-up/drop-off activity into account, as it had yet to emerge as a major issue (*11*). However, municipalities are quickly adapting to changing curbside pressures. Butrina et al. employed a semi-structured interviewing approach to elicit how municipalities are adapting to new pressures on their curbsides (*12*). Having interviewed senior staff responsible for curbside policy of 10 large U.S. municipalities, they documented a trend of organizational restructuring to include curbside management teams more formally, with the majority of interviewees also reporting increased staffing. Respondents reported that operational failures at their curbsides (e.g., demand in excess of capacity) have impacts on safety, capacity, and emergency vehicle mobility.

In response to the growing competition for curb space, some cities are calling the curbside "flex" space and starting to be more intentional about defining curbside uses. Kong et al. proposed a framework for modeling intermodal competition for curb space to support curb managers to move toward maximizing the aspects of economic welfare that relate to curb access (*13*). Inspired by the classic bid-rent model of urban land use, this framework demonstrates the type of adaptive and evolving approach needed to maximize benefits from increasingly dynamic curb management strategies. Ma et al. offered an empirical approach to repurposing the curb, providing municipalities with the ability to develop the means to eventually liberate this public space from parked vehicles and repurpose it for the benefit of a larger community (*14*). Their analysis suggested recommendations for future usage of existing curb spaces and ways to ensure curb parking is ready for shared autonomous vehicles. A 2018 report by the International Transport Forum (ITF) presents an overview of curbside management challenges that cities around the world are increasingly faced with, as shared mobility services and urban goods deliveries continue to rise (*15*). Through quantitative modeling and expert input, ITF analyzed the relative efficiency, contribution to city policy objectives, and implications on city revenues of shifting curb space use away from parking toward passenger and commercial loading. The report suggests that curb space should be flexible and dynamic to adapt to different uses over the course of the day. It also showed that, when TNC vehicles have better access to the curb, traffic congestion could decrease as the percentage of shared rides increases. A Los Angeles study examined how productively TNC vehicles utilize different curb zones compared with other motorized vehicles, and how curb zone allocation affects TNC vehicles' access to the curb, and concluded that the growth of ridesourcing in cities justifies reallocating curb parking for loading and public spaces (*16*). The results showed that, on a busy corridor, a PLZ served four times as many passengers per hour as a parking space, and that TNC vehicles spent a fraction of the time spent at the curb by private cars per passenger transported. It was also found that occupancy of the corridor curb parking zones by private cars and abuse of time limits (mainly by private cars) in loading zones had encouraged illegal parking activity by TNC vehicles.

In practice, cities are mostly handling these changes in the demand for curbside access by reallocating portions of the curb from traditional uses, such as parking, to uses by new mobility services such as ridesourcing and micromobility. Because of the rapidly growing complexity of curbside management and the lack of standard analytical approaches, however, such actions are being done on an ad-hoc basis. The Institute of Transportation Engineers recently developed a curbside management practitioner's guide to provide guidance on best practices for curb space allocation policy and implementation based primarily on the outcomes of strategies tested in various cities (*17*). It presents a framework and toolbox for analyzing and optimizing curb space with the aim of prioritizing and maximizing community values and safety. A series of reports by Shaheen et al. also lay out strategies for public right-of-way management and present areas in which local and regional governments can influence TNC use of on-street parking and curb space, including pricing, public-private partnerships, rights-of-way allocation, zoning regulations, tax incentives, signage, and advertizing (*3*, *18*, *19*). They provide guiding principles and a policy toolkit for public agencies allocating rights-of-way for TNCs and other shared mobility modes, followed by example policies and best practices.

In the U.S., leading cities like Washington D.C. and San Francisco have started to find ways to manage curbs to avoid compounding congestion. The District Department of Transportation applied a curbside management policy in the Dupont Circle Nightlife Pilot in 2018, reallocating parking zones on and around Connecticut Ave NW to PLZs. The reallocated PLZs were designed to address traffic and pedestrian safety concerns generated by the growing late-night activity at the Dupont area restaurants and bars, and were effective 10:00 p.m.–7:00 a.m. on Thursday, Friday, and Saturday nights (*20*). In a San Francisco study, data was collected at several locations with moderate to high passenger loading activity and a mixture of adjacent land uses/neighborhoods and roadway characteristics to develop broad strategies to improve curb space productivity for a variety of roadway typologies (*21*). Having applied the strategies to five study locations, it was found that while each case study location has a unique blend of roadway characteristics, surrounding land uses, and community priorities, providing additional opportunities for passenger loading to occur at the curb would improve traffic flow, reduce pedestrian exposure to traffic, and bring people to and from these areas in a more efficient manner.

In Seattle, broad concerns about rising ridesourcing use, congestion, safety, and effective curb use have led to calls for the city to consider allocating more curb space for passenger pick-up and drop-off. According to an analysis by the Seattle Times (*22*), TNC ridership in the Seattle region has grown to more than five times the level it was at the beginning of 2015, providing, on average, more than 91,000 rides a day in 2018. Those rides were equivalent to roughly one-quarter of the city's public transit ridership at the time. Additionally, Uber and Lyft trips are heavily concentrated in the city's densest neighborhoods, where nearly 40,000 rides a day start in ZIP codes covering downtown and nearby areas. To try to mitigate the impacts of TNC vehicles on traffic, by managing TNC driver stops when picking up and dropping off passengers, this study was born, focusing on the South Lake Union (SLU) area. The city proposed a strategy of increasing PLZ spaces while Uber and Lyft implemented a geofence, which directs their drivers and passengers to designated pick-up and drop-off locations on a block. (Normally, drivers pick up or drop off passengers at any location requested via the ridesourcing app.)

For this research, an array of data on street and curb activity along three study blockfaces in SLU was collected, using video and sensor technology as well as in-person observations. Data were collected in three phases between December 2018 and January 2019: (i) the baseline, (ii) after the new PLZs were added, and (iii) after geofencing was added to the expanded PLZs. The study examines the impact of the increased PLZs and geofencing on local traffic and TNC operation by asking the extent to which:

- TNC vehicles' dwell time changed
- it was easier or harder for TNC passengers and drivers to find each other
- TNC drivers' compliance changed in using curb space for passenger pick-up and drop-off versus stopping in the travel lane
- TNC drivers' decision to stop in the travel lane is a consequence of curb availability
- traffic speed in the study area changed
- traffic safety in the study area changed
- the added PLZs were utilized.

The study also investigates:

- TNC share of total traffic volume in the study area, and
- how TNC passenger satisfaction changed in response to the implemented strategies.

More details about the study area and the data collection efforts conducted for this study are described respectively in the second and third sections of this paper. The major study findings are presented in the fourth section, answering the above research questions. The final section presents the concluding remarks and policy recommendations.

Study Area

This study was conducted in the SLU area of Seattle, WA. SLU is the site of the main campus for Amazon, the online retail company, and Amazon reports high rates of ridesourcing use for employee commutes in this area. The center city neighborhood has heavy vehicle traffic and pedestrian activity and is characterized by multiple construction sites and two-lane streets with low speed limits (25 mph). Drivers tend to drive at relatively slow speeds, navigating around high pedestrian and jaywalking volumes, and seem relatively comfortable stopping in the travel lane for picking up or dropping off passengers.

Over the course of this study, the Seattle Department of Transportation (SDOT) made changes to paid parking zones in the area with the intention of influencing traffic flow. The changes include (a) installing signs to reduce the paid parking time limit and to change curb allocation from paid parking/food truck to PLZ/food truck, and (b) geofencing for pick-up and drop-off activities. PLZs are intended for use by TNC vehicles or other vehicles picking up or dropping off passengers. Three blockfaces on Boren Ave N were selected to study more closely (Figure 1). These blockfaces experience intense pick-up/drop-off activity, as well as high pedestrian volumes, during peak hours. Total PLZ curb length on these blockfaces was expanded from 20 ft (easily filled by one to two vehicles) to 274 ft.

Curb reallocation and sign installation happened on December 10, 2018, and the new PLZs were effective 7:00–10:00 a.m. and 2:00–7:00 p.m. Monday through Friday. Permitted food trucks were authorized to use the curb between 10:00 a.m. and 2:00 p.m. on weekdays. In addition to curb reallocations, two ridesourcing companies, Uber and Lyft, implemented a geofence in the area for passenger pick-ups and drop-offs. Implemented in the Uber and Lyft applications, geofencing directed TNC drivers and passengers to designated locations along a block (as opposed to an address requested by a rider via the ridesourcing app) with the purpose of regulating TNC vehicle operations. Geofencing was implemented on December 24, 2018. The geofence area and the designated pick-up/drop-off locations are shown in Figure 1.

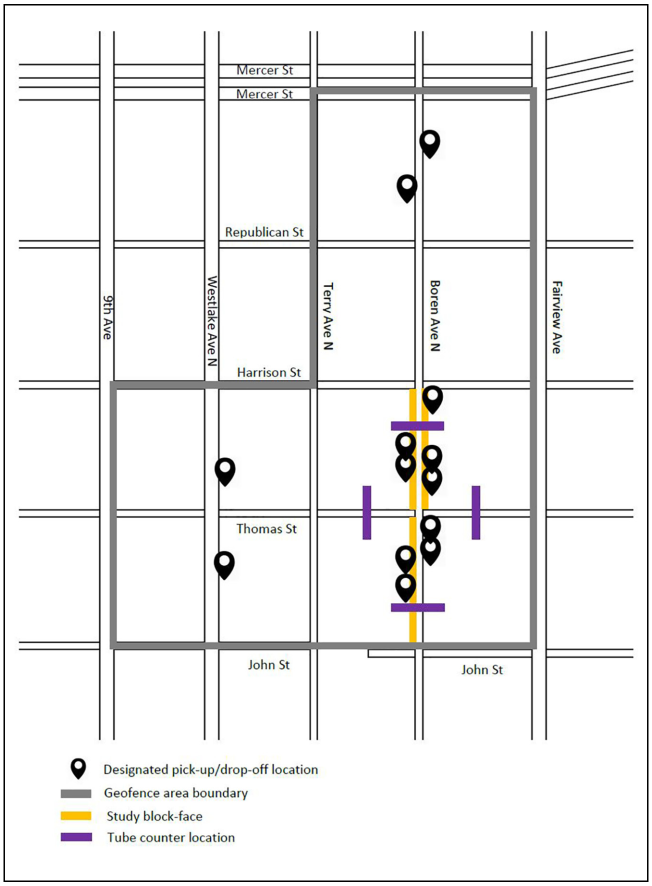

Figure 1. Study blockfaces along with the geofence area and designated pick-up/drop-off locations implemented in South Lake Union (SLU) area of Seattle, WA.

Uber applied geofencing all day, while Lyft limited it to 7:00–10:00 a.m. and 2:00–7:00 p.m. to match the signs.

It should be noted that several outreach strategies were used to inform travelers of the changes. In addition to the signs installed by SDOT, sandwich board signs were placed on sidewalks to increase visibility of the newly designated pick-up/drop-off locations. Amazon also informed its employees of the geofence and the designated pick-up/drop-off locations via email announcements and flyers posted in the buildings.

Data Collection

Data collection was conducted in three phases as explained in Table 1. The collected data elements are explained in the following subsections.

Curb Activity and Traffic Speed/Flow Data

Curb activity data was collected through capturing video and reducing the videos into quantitative measures on the study blockfaces for 8:00–10:00 a.m. and 2:00–6:00 p.m. every day over the three phases of data collection. Some of the quantitative measures include event type (passenger pick-up or drop-off, vehicle park or exit parking), event start and end time, event location, vehicle type, number of passengers boarding/alighting, driver's exit/return time, and conflicts (a situation where a user of the road [vehicle, bike, or pedestrian] is interrupted and forced to alter their path).

Traffic speed and flow data were collected through installing tube counters in the study area and converting tube data into quantitative measures of speed and volume for 24 h every day over the three phases of data collection. The tubes were installed in four locations as shown in Figure 1.

Field Observations

Additional data were collected by human observers to enrich interpretation of curb activity and traffic speed/flow data, and to add depth and insight into the behaviors that might be missed by video or sensor data. The collected observations included the number of pedestrians crossing the street at non-crosswalk locations and on-street parking occupancy (i.e., number of vehicles parked at the curb). The observations were conducted along the study blocks for one morning period (7:45–10:15 a.m.) and two afternoon periods (4:15–6:45 p.m.) in each week of data collection.

To be consistent across all observations, data collection forms were designed to be filled by human observers. Data collectors were given hard copies of the forms along with maps of the study area that marked their duty locations. To collect data on pedestrian crossings, two data collectors were assigned to each study block, each covering half the block. On the data collection form, they were asked to record the number of pedestrians crossing the street at non-crosswalk locations in three categories—being picked up, being dropped off, or neither—in 5-min intervals. For on-street parking occupancy, data collectors were given walking itineraries with 8–10 blockfaces each, and asked to record the number of vehicles parked at the curb along those blockfaces every 15 min during their shifts. Each form also had an additional section, where data collectors could document any general observation or leave comments about unclear situations.

Passenger Survey

To collect additional data on travel behaviors and experiences of passengers, an intercept survey was designed and conducted in the study area. The survey questionnaire was approved by the University of Washington institutional review board, and included questions on socio-

Table 1. Three Phases of Data Collection

Phase	Description	Dates
1: Baseline	Control phase (no changes)	Monday December 3, 2018–Friday December 7, 2018
2: Added PLZs	Signs were installed to change paid parking to PLZ at morning and afternoon peak times	Monday December 17, 2018–Friday December 21, 2018
3: Added PLZs + geofence	Curb change signs remained, and TNCs implemented the geofence	Monday January 7, 2019–Friday January 11, 2019

Note: PLZ = passenger load zone; TNC = transportation network company.

demographic and trip-related information of the TNC passengers, as well as their satisfaction rate with pick-up/drop-off.

The survey was hosted online in a format that could be easily accessed and filled out on a cell phone. Surveyors present in the study area handed a card with the survey URL and a QR code to passengers waiting to be picked up or those being dropped off to fill out later. To encourage survey participation, a raffle prize of an Apple Watch was offered.

The survey was administered at several locations in the neighborhood, which corresponded to the designated pick-up/drop-off points. The survey was conducted during 17 morning (8:30–10:30 a.m.) and evening (5:00–7:00 p.m.) periods each week. Surveying on locations other than the three study blockfaces was done over the same dates as Phases 1 and 3 of data collection; however, since intercepting passengers would affect the vehicle stop time and traffic flow, the survey on the three study blockfaces was conducted on Monday and Tuesday of the week following the data collection phases.

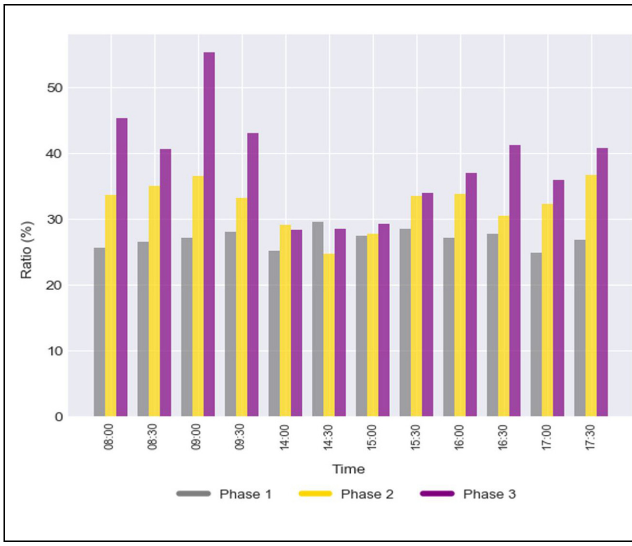

Figure 2. Average passenger pick-up/drop-off activity as percentage of traffic volume (in 30-min intervals) for all three blockfaces and both directions.

Findings

TNC Demand and Operation

Share of Total Traffic Volume. Figure 2 shows the average percentage of passenger pick-ups/drop-offs versus traffic volume in 30-min intervals for each phase of data collection. Passenger pick-ups/drop-offs constituted 25%–55% of traffic volume on the studied blockfaces, and increased from an average of 29% (8.7 out of 30.2 vehicles) in Phase 1 to 32% (11.0 out of 34.3 vehicles) and 39% (13.9 out of 35.4 vehicles) in Phases 2 and 3, respectively. The standard deviation of the percentage of passenger pick-ups/drop-offs throughout the day also increased from 1.3% in Phase 1 to 3.5% and 7.6% in Phases 2 and 3, respectively. Recall that this area was selected because of high TNC vehicle volume, so these rates should not be interpreted as representative of all Seattle neighborhoods. Moreover, the implementation of geofencing may have drawn pick-up/drop-off activity to the study area and away from nearby arterial streets during Phase 3.

Dwell Time. One of the research questions in this study was the extent to which vehicle dwell time changed after more PLZs were added and geofencing was implemented.

Figure 3 shows the cumulative distribution functions of vehicle dwell times for pick-up and drop-off at the curb across the three phases of study. As can be seen in Figure 3*a*, passenger pick-ups at the curb were faster in Phase 3 than in Phases 1 and 2, and based on a pairwise Kolmogorov–Smirnov test and a three-sample Anderson–Darling test, the differences in pick-up dwell time distributions between Phase 3 and the other two phases are statistically significant ($p < 0.015$). In Phase 3, 80% of pick-up dwell times were under 3 min and 18 s, while the dwell time value for the same proportion for Phases 1 and 2 was approximately 4 min and 30 s. Similar to pick-ups, drop-

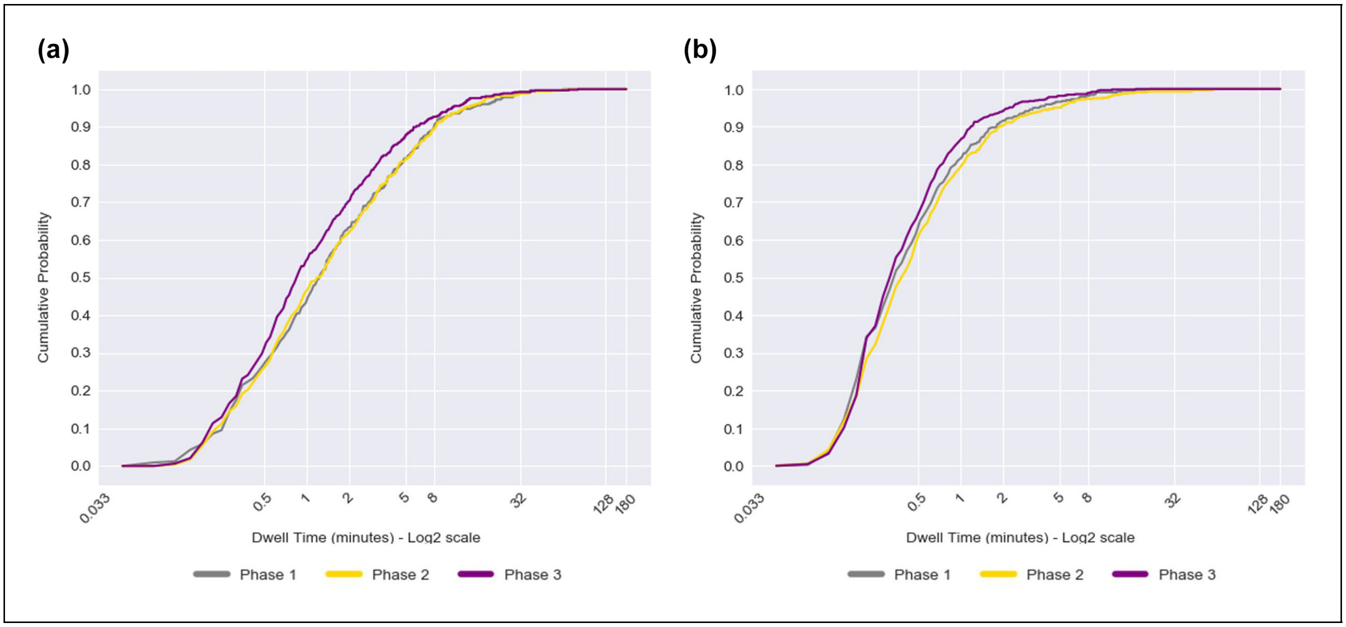

Figure 3. Empirical dwell time distributions of: (*a*) passenger pick-ups and (*b*) passenger drop-offs at curb for the three phases of study (all three blockfaces and both directions).

offs were faster in Phase 3 than in Phases 1 and 2 (Figure 3*b*), and a pairwise Kolmogorov-Smirnov test and a three-sample Anderson-Darling test showed that the difference in drop-off dwell time distributions between Phases 2 and 3 was statistically significant ($p < 0.02$). In Phase 3, 90% of drop-off dwell times were under 1 min and 12 s, while the dwell time value for the same proportion for Phase 2 was 1 min and 54 s.

The results also showed that drop-offs happened faster than pick-ups. Half of the drop-offs lasted 11 s or less, and 90% were under 1 min and 12 s. For pick-ups, on the other hand, half were under 35 s and 90% were under 4 min and 41 s. Based on a Kolmogorov–Smirnov test, the difference between the two distributions was statistically significant ($p < 0.001$).

Investigating dwell times based on the stop location showed that pick-ups or drop-offs were the fastest when they took place in the travel lane. Pick-ups and drop-offs occurring somewhere between the travel lane and curb (half-and-half) were the next quickest, while those at the curb were the slowest. The median dwell times for stops happening in the travel lane, half-and-half, and at the curb were respectively 14, 20, and 33 s. Of the pick-ups/drop-offs occurring in the travel lane, 90% took less than 41 s, while the corresponding value for those happening somewhere between the travel lane and curb and at the curb were 1 min and 34 s, and 4 min and 35 s, respectively. Based on a pairwise Kolmogorov–Smirnov test and a three-sample Anderson–Darling test, the differences between dwell time distributions were statistically significant ($p < 0.001$).

Parking Choice and Compliance. To study whether adding new PLZs and geofencing increased compliant pick-up/drop-off behaviors (in terms of using curb space versus stopping in the travel lane), stop locations were grouped into in-lane, authorized curb (at the curb or half-and-half in a PLZ), and unauthorized curb (at the curb or half-and-half in a space with an allocation other than PLZ, such as paid parking). Figure 4 shows compliance for pick-up and drop-off operations. As can be seen, compliance in stop location choice looks similar for pick-ups and drop-offs. In both cases, the percentage of unauthorized stops at the curb significantly dropped in Phases 2 and 3 compared with Phase 1. When considering the cause of this change, however, it should be noted that in Phases 2 and 3 the available PLZ spaces were about 14 times more than in Phase 1. However, the percentage of in-lane stops also decreased in Phases 2 and 3 compared with Phase 1, and according to a Chi-square test, these differences are significant for both pick-up ($p \asymp 0$) and drop-off ($p < 0.01$) operations.

The correlation between a driver's choice to stop in the travel lane and the number of vehicles occupying the PLZs at the time of the vehicle arrival at the blockface was also studied, to see whether the driver's choice of in-lane stop is a consequence of a lack of curb availability. The results showed that in Phase 1, arriving vehicles observed either a completely free PLZ or one vehicle parked; this is because in the baseline only one parking space was allocated as PLZ. During the baseline, when the PLZ was free, only 9% of vehicles chose to stop in the travel lane, while when it was occupied, 15% of

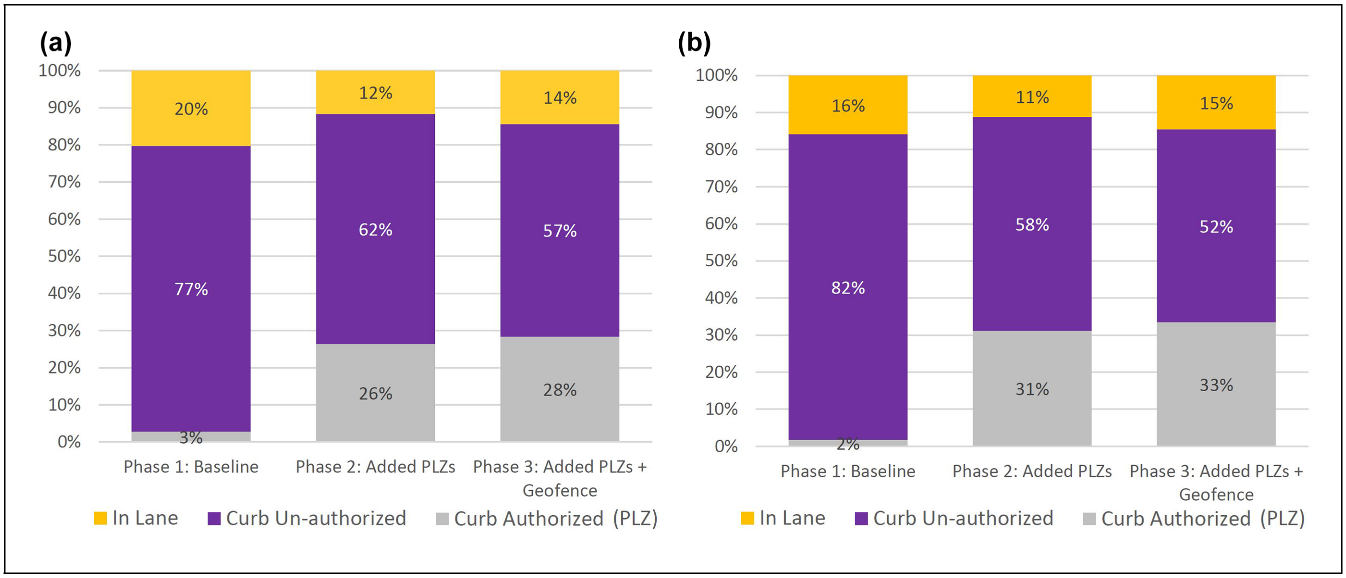

Figure 4. Compliance in stop location choice for (*a*) pick-ups and (*b*) drop-offs.
Note: PLZ = passenger loading zone.

vehicles stopped in the travel lane and the rest stopped at paid parking spaces. During Phases 2 and 3, more PLZs were added, and therefore there were cases where two and more vehicles were occupying the PLZs on a blockface. The results showed that an increase in the PLZ occupancy increased the likelihood of stopping in the travel lane. In Phase 3, the percentage of vehicles that stopped in the travel lane when PLZs were empty was 10%, while that percentage increased to 17%, 20%, and 26% respectively for occupancy levels of one, two, and three or more vehicles. Phase 2 showed a similar trend as Phase 3, except that in Phase 2 the increases in the percentage of in-lane stops for occupancy levels of one and two vehicles were larger than that of the three or more vehicles occupancy level: the percentage of vehicles stopped in the travel lane increased from 7% when PLZs were empty to 14%, 16%, and 11% when PLZs were occupied by one, two, and three or more vehicles, respectively. However, it should be noted that since very few vehicles experienced the PLZ occupancy level of three or more vehicles on arrival, the confidence intervals of in-lane stopping percentages for that occupancy level are much larger than those for the one- or two-vehicle occupancy levels.

In general, vehicles arriving to pick up or drop off passengers rarely experienced high PLZ occupancy levels (three or more vehicles) in our study area; however, in almost all cases, an increase in the PLZ occupancy increased the likelihood of stopping in the travel lane. It is also worth noting that in all phases, 7%–10% of the arriving vehicles still chose to stop in the travel lane even when PLZs were empty.

Curb Occupancy and Curb Space Productivity. To study the extent to which the added PLZs were utilized, the occupancy of PLZs across the three phases of data collection was studied. The total curb length dedicated to PLZ was 20 ft in the baseline and 274 ft in Phases 2 and 3. To calculate the space used by vehicles and compare it with the PLZ length, a representative length for each vehicle type was considered: 15 ft for passenger vehicles, TNCs and taxis, 22 ft for large passenger vehicles, and 30 ft for trucks (*23–25*). The number of vehicles using the PLZ spaces were then aggregated into 30-min intervals across all days of a week, and converted into a standard PLZ space.

Figure 5 shows the average occupancy of PLZs during the study time periods (8:00–10:00 a.m. and 2:00–6:00 p.m.) in 30-min intervals. In Phase 1 higher occupancy rates and larger variability (ranging from 3% to 100%) were observed, which is because of the small PLZ space in the baseline that could be easily filled with one or two vehicles. In Phases 2 and 3, however, the occupancy rate barely rose over 20%, except for an evening period (5:00–5:30 p.m.) in Phase 2, where there was a spike in occupancy and approximately 50% of the space was occupied. Overall, Phase 2 showed lower occupancy rates than Phase 3 in the first half of the morning peak (8:00–9:00 a.m.) and in the second half of the afternoon peak (4:00–6:00 p.m.). The average PLZ occupancy rate of 20% or lower (even during peak commute hours) suggests that the new allocation of PLZ spaces was much more than what was needed to meet observed demand.

Another measure for studying curb utilization is the productivity of the curb space, which is calculated as follows:

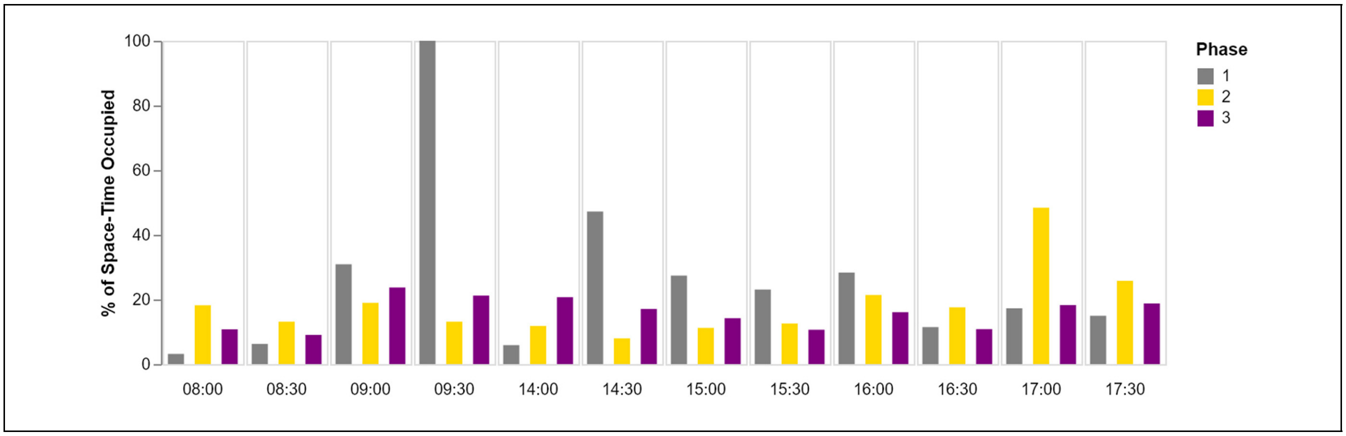

Figure 5. Average percentage of passenger loading zones (PLZs) being occupied in 30-min intervals.

Table 2. Average Curb Space Productivity of Passenger Loading Zones (PLZs) and Paid Parking Spaces

Time period	Phase	Old and new PLZs (passenger/ft/h)	Fixed paid parking (passenger/ft/h)
Morning	1	0.14	0.06
	2	0.14	0.12
	3	0.17	0.15
Afternoon	1	0.05	0.08
	2	0.09	0.10
	3	0.10	0.11

$$\text{Curb space productivity} = \frac{\text{Total passengers served at the curb}}{\text{Curb length} \times \text{Duration of study period}}$$

where Curb length refers to the length of the curb where the vehicle stops occurred; Duration of study period refers to either the morning (2 h) or afternoon (4 h) periods when data was being collected; and Total passengers served at the curb is calculated as the sum of:

- the number of passengers picked up,
- the number of passengers dropped off,
- the number of individuals served by the vehicles that either parked or exited parking during the study period, and
- two times the number of individuals served by the vehicles that both parked and exited parking during the study period—as these vehicles both unloaded and loaded individuals.

Curb space productivity was estimated for two curb segments in the study area:

- Old and new PLZs: This includes all the 274 ft of curb space along the study blockfaces that was allocated to PLZ during Phases 2 and 3. During Phase 1, this curb length constitutes 20 ft of PLZ and 254 ft of 2-h paid parking.
- Fixed paid parking: This includes approximately 216 ft of curb space along the study blockfaces that remained as 2-h paid parking across all three phases of study.

Table 2 shows average productivity of the above curb segments during the morning and afternoon time periods on a weekday. For both segments, space productivity increased from Phase 1 to Phases 2 and 3. For the PLZ segment, across all phases, space productivity was higher in the morning than in the afternoon, while this is not the case for the fixed paid parking segment.

The low productivity rates suggest over-supply of PLZ spaces. While the PLZ curb length was increased by approximately 14 times, it did not translate into a proportional increase in curb space productivity.

Impacts on Traffic

Impacts on Speed. To explore the extent to which the changes of adding PLZs and geofencing affected traffic speed, a regression analysis was performed, taking into account several variables such as traffic volume, number of passenger pick-ups and drop-offs, and time of day.

Table 3. Average Conflict Rates

Time period	Phase	Number of conflicts/total pick-ups and drop-offs	Number of conflicts/total traffic volume
Morning	1	0.12	0.03
	2	0.14	0.03
	3	0.14	0.05
Afternoon	1	0.16	0.03
	2	0.17	0.04
	3	0.17	0.04

The log of traffic speed was modeled as a function of various combinations of traffic volume, number of passenger pick-ups and drop-offs, time of day, and indicators for the presence of PLZs and geofencing. The regression parameters were estimated through the ordinary least squares (OLS) method, and the heteroskedasticity and autocorrelation consistent (HAC) method was used for estimating standard errors. The models did not find a statistically significant impact on travel speed from the introduction of either PLZs or geofencing. On the other hand, field observations showed that myriad factors affect neighborhood congestion, including:

- *Regional traffic congestion on nearby arterials*—There is high traffic volume on arterials in the proximity of the study area. These arterials become very congested, especially during the afternoon peak, with spillbacks going onto local streets, which in turn result in deterioration in rule-following and some dangerous driving behavior.
- *Parking garages*—There are three parking garages from which vehicles exit onto streets, causing long queues and traffic congestion on local streets. Having divided the hourly vehicle flow from/to these parking garages to the traffic volume on the block where the garage's entrance/exit is located, it was found that vehicles entering/exiting the garages are equal to 35%–60% of street vehicles in the morning and 20%–40% of those in the afternoon.
- *Slow speed limits and less formal infrastructure*—The speed limit on the study blocks is 25 mph, and there are stop signs at all intersections. Semi-permanent curbs (hand-formed asphalt as opposed to formed concrete), curbs lacking appropriate street paint, curb bulbs on the two sides of the street which reduce the crossing distance, and pick-up/drop-off sandwich board signs (that were placed on sidewalks to increase the visibility of designated locations) create a sense of less formality for the neighborhood infrastructure.
- *High levels of unorganized pedestrian activity*—There are large multi-story office buildings and many bars/restaurants in the study area, which drive high levels of pedestrian activity. Moreover, high pedestrian volumes (400–500 per hour on average) cross the street at points where there is no crosswalk, which could be because of slow speed limits and less formal infrastructure explained above. Passengers picked up/dropped off constitute a small fraction (5%–7%) of the total pedestrian crossings, but high rates of passengers (30%–40%) cross the street at non-crosswalk locations, as part of the pick-up/drop-off operation.

Impacts on Safety. To investigate the impacts of changes on traffic safety in the study area, the number of conflicts before and after the changes was studied. Conflicts are defined as a situation where a user of the road (vehicle, bike, or pedestrian) is interrupted and forced to alter their path. The conflict categories were defined as: vehicle-vehicle, vehicle-bike, vehicle-pedestrian, and pass through the oncoming traffic lane.

Table 3 shows the average number of conflicts divided by the total number of passenger pick-ups and drop-offs and by the total traffic volume, in the morning and afternoon periods. Either way, the changes in conflict rates across the three phases of study are not significant. The passenger pick-up/drop-off events were also modeled as a series of Bernoulli trials, in which each event outcome can be a "Conflict" or "No conflict." A binomial regression of the probability of an event resulting in a conflict was then derived as a function of several explanatory variables, including traffic volume, number of pick-ups and drop-offs, and indicators for the presence of PLZs and geofencing. Nevertheless, the results showed no statistically significant effect of adding PLZs or geofencing on the probability of a pick-up/drop-off event causing a conflict.

Impacts on TNC Passengers

One of the main research questions in the present study was how the TNC passengers responded to the changes of adding PLZs and implementing the geofence. To answer this, a passenger intercept survey was conducted, as explained in the Data Collection section. The survey response rate was relatively high, with 19% for Phase 1 (a total of 52 responses) and 24% for Phase 3 (a total of 64 responses).

Summary Statistics. Table 4 presents a summary of the socio-demographic and trip characteristics of TNC users in the area. As can be seen, the sample skews toward male, young (25–34 years old), higher-income (65% or more of the respondents reported an individual annual income of $100,000) individuals. About 40%–50% of our sample reported making a work-related trip, and more than half of the sample were frequent TNC users (defined as using TNC services at least once a week). In both phases, more than half of the respondents reported having used a private economy ride (e.g., UberX, Lyft), and 70% or more took a ridesourcing service all the way from origin to destination on their trip. Among those who used ridesourcing in connection with another transportation mode for their trip, a majority reported linking with public transit (bus, light rail, streetcar). Nearly half the respondents stated that they would have taken public transit if ridesourcing were not available, and about one-third said they would have walked. This is consistent with previous studies that have reported about 40%–60% of ridesourcing trips substitute for transit, walk, or bike trips or would not have been made at all (*9, 10, 26, 27*).

It is worth noting that there were 470 ft (~30 spaces) of on-street metered parking in the study area in Phase 1, and 216 ft (~15 spaces) in Phases 2 and 3, each costing $3–4 per hour. There were also three large parking garages in the study area, which cost $3–4 for the first hour and $21–26 daily. A one-way transit ride costs $2.75.

Satisfaction. Figure 6 shows passenger satisfaction statistics for pick-ups and drop-offs in Phases 1 and 3. With both pick-ups and drop-offs, passenger satisfaction increased after adding PLZs and implementing the geofence. Although one person rated his/her pick-up experience as "Awful" in Phase 3, 79% of passengers rated their pick-up experience between "Excellent" and "Good" in that phase; whereas the corresponding number for Phase 1 is 72%. This difference is even larger for drop-offs: all passengers rated their drop-off experience in Phase 3 at least "Good," and 97% rated it either "Excellent" or "Very Good"; whereas in Phase 1, only 89% of passengers rated their drop-off experience at least "Good."

To test the significance of changes in passenger satisfaction between Phase 3 and the baseline, an ordinal logistic regression model was applied to the survey data. Table 5 shows the analysis results for a single-variate model, where the only predictor is the study phase, as well as for a multi-variate model, where in addition to the study phase other variables are also considered as predictors. As can be seen from the *t*-values, in both models the phase variable was positive and significant, which shows that the added PLZs and geofencing significantly contributed to the passenger satisfaction.

Conclusion

This study evaluated two strategies to manage TNC driver stops when picking up and dropping off passengers, with the goal of improving traffic flow in the vehicle-congested and pedestrian-heavy SLU area of Seattle, WA. The strategies included providing additional PLZs and implementing a geofence, which directs TNC drivers and passengers to designated pick-up and drop-off locations on a block.

The aim of providing ample designated pick-up and drop-off locations along the curb was to reduce (a) the frequency with which TNC drivers stop in the travel lane to pick up or drop off passengers and (b) the time they stay stopped there. The findings show a reduction in both in-lane stops and dwell time in the wake of the expanded PLZs and geofencing. In other words, by these measures the strategy was a success. However, 7%–10% of the drivers still stopped in the travel lane even when PLZs were empty. So, to eliminate in-lane stops for pick-up and drop-off activities, providing curb space and geofencing alone may not be sufficient. It was also shown that it is possible to over-supply curb space in a reallocation like this. While curb utilization increased after adding PLZs and geofencing, average PLZ occupancy was fairly low in the post-treatment period, because the allocation of PLZ spaces was much more than what was needed to meet observed demand. A careful assessment of likely demand should be conducted before allocating curb spaces to PLZs, and should be revisited regularly as the shared mobility market is evolving quickly.

The two strategies, however, had no observable impact on traffic safety or roadway travel speed. This is perhaps unsurprising, given that drivers in the study area tend to drive at relatively slow speeds anyway, navigating around high pedestrian and jaywalker volumes, and seem relatively comfortable stopping in the middle of the street for short periods of time. Because of the nature of area traffic, this seems to have relatively little impact on other drivers. Drivers appear to anticipate both this behavior and the high volumes of vehicles moving onto/off the curb and into/out of driveways and alleys.

The study finds that while TNCs contribute significantly to the overall traffic volume in SLU, TNC pick-up and drop-off activity is not the primary cause of

Table 4. Summary of Socio-Demographic and Trip Characteristics of TNC Users in the Study Area

Question	Categories	Phase 1	Phase 3
What is your gender?	Female	23%	45%
	Male	73%	55%
	Prefer not to answer	4%	0%
What is your age?	18–24	13%	8%
	25–34	56%	72%
	35–44	25%	19%
	45–64	6%	2%
What is your personal annual income level?	Under $15,000	4%	6%
	$15,000–$29,999	0%	0%
	$30,000–$49,999	6%	3%
	$50,000–$74,999	10%	6%
	$75,000–$99,999	15%	11%
	$100,000–$150,000	29%	50%
	$150,000–$200,000	19%	14%
	Over $200,000	17%	9%
Which of the following best describes your current job situation?	Employed work from home	10%	2%
	Employed outside home	85%	97%
	Student	4%	2%
	Retired	2%	0%
What was the purpose of your trip?	Home	25%	25%
	Work	38%	53%
	Personal business (bank, doctor appointment)	10%	3%
	Recreation/meal/social	19%	16%
	Shopping	2%	0%
	Other (P&R, hotel, gym)	6%	3%
What service did you request?	Private economy ride (UberX, Lyft)	58%	51%
	Shared door-to-door ride (Uber Pool, Lyft Shared)	27%	42%
	Shared with a short walk (Express Pool)	13%	5%
	Premium/Luxury vehicles (Uber Black, Uber Select, Lyft Lux, Lyft Lux Black)	0%	2%
	Extra space (Uber XL, Black SUV, Lyft XL, Lyft Lux Black XL)	2%	0%
If you didn't use ridesourcing (e.g., Uber or Lyft) all the way from your origin to destination on this trip, what was the other mode of transportation that you used? (*This was a two-part question.*)	Just ridesourcing	77%	69%
	Bike	2%	2%
	Drive personal car	6%	5%
	Car share	2%	3%
	Picked up/dropped off (by a friend or family member)	2%	3%
	Public transit (bus, light rail, streetcar)	12%	19%
How would you have made this trip if ridesourcing (e.g., Uber or Lyft) were not available?	Walk	29%	36%
	Bike	4%	2%
	Drive personal car	10%	8%
	Car share	8%	6%
	Picked up/dropped off (by a friend or family member)	2%	3%
	Public transit (bus, light rail, streetcar)	48%	45%
How often do you generally use ridesourcing services (e.g., Uber or Lyft)?	Daily	13%	23%
	A few times a week	27%	42%
	Weekly	13%	8%
	A few times a month	33%	22%
	Monthly	4%	2%
	Less than once a month	10%	3%

Note: P&R = park-and-ride; TNC = transportation network company.

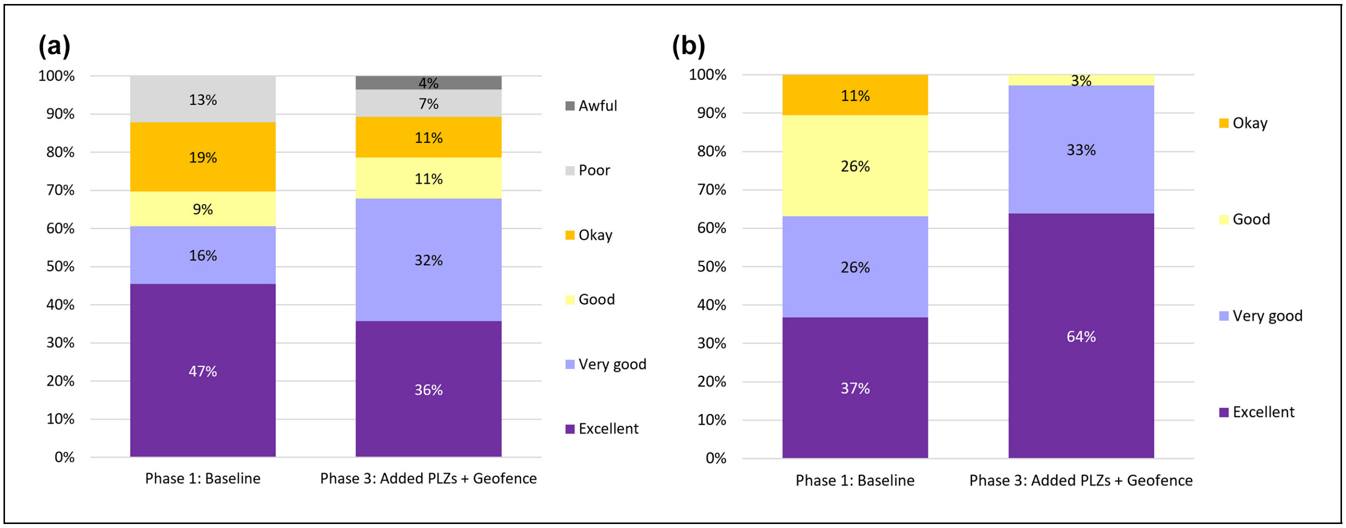

Figure 6. Passenger satisfaction for (*a*) pick-up and (*b*) drop-off behaviors ($n = 55$). The rating scale was the same for pick-ups and drop-offs, but there were no "poor" or "awful" ratings for drop-offs.
Note: PLZ = passenger load zone.

Table 5. Regression Analysis Results for the Effect of Implemented Strategies on Passenger Satisfaction

	Multi-variate model			Single-variate model			
Coefficients							
	Value	Standard error	*t*-value		Value	Standard error	*t*-value
Pick-up	0.8901	0.6827	1.304				
Phase: 3	0.6954	0.3994	1.741	Phase: 3	0.6462	0.3515	1.838
Purpose: Work	2.5395	0.8072	3.146				
Purpose: Personal business	−1.0555	0.7322	−1.442				
Purpose: Meal/social	1.2833	0.5984	2.145				
TNC usage frequency	−0.1612	0.1407	−1.145				
Annual Income > $100K	−0.7118	0.4812	−1.479				
No mode connection (only TNC)	−1.3035	0.4971	−2.622				
Transfer to/from transit	0.9767	0.7489	1.304				
Intercepts							
	Value	Standard error	*t*-value		Value	Standard error	*t*-value
Awful|Poor	−5.3257	1.4676	−3.6288	Awful|Poor	−4.4441	1.0104	−4.3983
Poor|Okay	−3.1906	1.1166	−2.8574	Poor|Okay	−2.4397	0.4202	−5.8058
Okay|Good	−1.8718	1.0495	−1.7836	Okay|Good	−1.3708	0.307	−4.4651
Good|Very Good	−1.0118	1.0365	−0.9762	Good|Very Good	−0.7057	0.2808	−2.5133
Very Good|Excellent	0.5543	1.034	0.536	Very Good|Excellent	0.4819	0.2776	1.7363
Model statistics							
Residual deviance		266.9282				311.818	
AIC		294.9282				323.818	
Log likelihood		−133.464 (df = 14)				−155.91 (df = 6)	

Note: AIC = akaike information criterion; TNC = transportation network company.

congestion there. Myriad factors affect neighborhood congestion, including high vehicle volume overall and bottlenecks moving out of the neighborhood onto regional arterials, causing spillbacks onto local streets.

Parking garages also exit vehicles onto streets that then feed into these clogged arterials. Of note is the study observation on high volumes of pedestrians (400–500 an hour on average) crossing the street at points where there was no crosswalk, and TNC passengers' contribution to that high volume. TNC passengers constituted a small fraction (5%–7%) of the total crossing pedestrians, though high rates of TNC passengers (30%–40%) cross the street at non-crosswalk locations.

The increased PLZ allocation and geofencing reduced dwell times, reduced the number of in-lane pick-ups/drop-offs, increased curb use compliance, and increased TNC passenger satisfaction. However, these outcomes will likely encourage commuters to use ridesourcing. Results of the study's passenger survey clearly show that ridesourcing service is attracting passengers who would have otherwise walked or used transit. If the end goal is to reduce traffic congestion, then measures to reduce—rather than encourage—ridesourcing and passenger car use as the predominant modes of commuting will yield benefits.

A limitation of this study relates to the timing and duration of data collection. The data collection for this study was timed to be completed before January 12, 2019, which marked the closure of the Alaskan Way viaduct, a major arterial in Seattle. For that reason, the study period and the intervals between phases of study were very short. It was also necessary to conduct the study in the months of December and January, which may not be representative of the full year. The short data collection windows tend to limit statistical power, and being conducted in the holiday season limits the generalizability of this analysis. However, the goal of this study was to set up an evaluation methodology, and to build the state of the practice around this topic. Longer intervals between the study phases would allow the behavior to settle and result in more meaningful observations. So for future studies, researchers are encouraged to allow more time to take scientifically significant observations and to be cognizant of seasonal variations.

While this research contributes important insights into the effects of curbside management strategies on traffic, the findings of this study apply to streets with comparable speed of traffic, mix of roadway users, and street design. Roadways with much higher traffic speeds or different geometric design could be anticipated to produce different results, and additional research in this area is strongly encouraged. Moreover, any initiative to manage the use of curbs and roads (by TNCs or others) is part of a city's broader transportation policy framework and goals, and whether the strategies this study analyzed are recommended depends on those goals.

Author Contributions

The authors confirm contribution to the paper as follows: study conception and design: A. Ranjbari, D. MacKenzie, A. Goodchild; data collection: A. Ranjbari, J. Machado; analysis and interpretation of results: A. Ranjbari, J. Machado, G. Dalla Chiara, D. MacKenzie, A. Goodchild; draft manuscript preparation: A. Ranjbari, J. Machado, G. Dalla Chiara. All authors reviewed the results and approved the final version of the manuscript.

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