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Transportation Network Companies' (TNC) Impacts and Potential on Airport Access

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Transportation Network Companies' (TNC) Impacts and Potential on Airport Access

DISSERTATION

submitted in partial satisfaction of the requirements
for the degree of

DOCTOR OF PHILOSOPHY

in Transportation Science

by

Karina Hermawan

Dissertation Committee:
Professor Amelia C. Regan, Chair
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2018

DEDICATION

This book is dedicated in memory of my dad, Herry Hermawan, and dear big brother, Sigit Hermawan. We are far but never apart.

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ABSTRACT OF THE DISSERTATION

Transportation Network Companies' (TNC) Impacts and Potential on Airport Access

By

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Doctor of Philosophy in Transportation Science

University of California, Irvine, 2018

Professor Amelia C. Regan, Chair

When Transportation Network Company (TNC) services first emerged, there was extensive discussion in the popular press and among academics about the benefits that these "shared" services would bring. TNC as a form of ground transportation to and from the airport in contrast, is less often studied or permitted. TNC operations at airports are highly controversial. At Los Angeles International Airport for example, Uber and Lyft could not conduct pickups until about seven years after they were founded. Still, research on both airports and TNCs rarely intersect. This dissertation aims to fill the gap in the literature and address such questions as: which and how many airports have various types of TNC service (standard, pooled)? How do they impact other modes, vehicle-occupancy, congestion, and access at airports? Can their service be modified (i.e. through pricing or service improvement) to encourage higher uses of shared modes? Using Uber and Lyft websites, it documents all airports in the U.S. and internationally that permit TNC service and the type of services available. It analyzes airport passenger surveys to evaluate how much TNC replaces and complements transit and the net effects at several airports. Also using the passenger survey, Google Maps Directions API, and other sources, it estimates travel time and costs of the different modes to the airport, builds a

discrete choice model of the access mode choices, and simulates various scenarios; some of the scenarios are a TNC price increase (to match the cost of taxis) or a price cut and travel time increase (to mimic Uber Pool and Lyft line which are carpool versions of TNCs). Finally, it assesses how a pooled TNC service to the airport would operate. We apply the pick-up and delivery problem to airport access requests (formed based on the airport passenger survey) and measure the number of private trips that would be eliminated when passengers are pooled. The motivation for understanding the consequences of making private TNCs more expensive, or pooled TNCs less expensive and more efficient (with shorter detours or travel time) is to identify effective tools to encourage modal shifts to vehicles with higher occupancy.

Chapter 1

Introduction

Uber was founded in 2009 and Lyft in 2012, but only recently were they allowed to pick up passengers at various airports. At Los Angeles International Airport (LAX), they finally could conduct pickups in January 2016 (about seven years later), while at other airports, they are still banned up to this day. Are Transportation Network Companies (TNC) growing rapidly and adding to congestion at the airport curbside? At the same time, are they helping increase access and enabling more shared modes use? TNC operations at airports are highly controversial, but not much about their impacts at airports is understood. This dissertation strives to add to the literature and investigates important questions regarding TNC services at airports, namely, how extensive are their services there in the U.S. and internationally? What are the different types of TNC services available? How do they impact other modes, vehicle-occupancy and congestion, and access? More importantly, is there potential to increase the use of shared modes to relieve congestion at the airport curbside?

The dissertation is organized as follows: after the introduction, there is a summary of the existing literature on TNC services in general and at airports (in chapter two). We also cover the literature on airport access and on the pick-up and delivery problem and its application to general trips or airport access trips (also in chapter two). In chapter three, we examine all US and international airports with major TNC service and the type of service. In the fourth chapter, we evaluate how much TNC is replacing and complementing shared modes and the net effects at LAX, San Francisco International Airport, and Oakland International Airport. The fifth and sixth chapters focus on understanding TNC's potential to increase the use of shared modes. In the fifth

chapter, we estimate travel time and costs of the different modes to LAX airport using Google Maps Directions API and other sources, build a discrete choice model of the access mode choices, and simulate various scenarios such as a TNC price increase (to match the cost of taxis) or a price cut and travel time increase (to mimic Uber Pool and Lyft line which are carpool or shared versions of TNCs). While airport access mode choices have been studied since the 1970's, this dissertation is the first to include TNC as one of the alternatives. Understanding passenger sensitivities to increased fares or discounted fares when the TNC ride is shared (to offset the minimal increase in travel time to pick-up and drop-off an additional passenger) can give insights to the implications of such policies. In chapter six, we simulate an optimized, multi-passenger TNC service to the airport. We apply the pick-up and delivery problem to airport access requests of air passengers traveling alone (created based on passenger survey data) and measure the number of private trips that would be eliminated by pooling. Following chapter six, the last chapter describes future research and extensions of this work.

Ultimately, the main objective of this research is to analyze TNC's impacts and investigate its potential to increase the use of high vehicle-occupancy vehicles or shared vehicles to alleviate congestion at airport terminals.

Chapter 2

Literature Review

2.1 TNC's Founding and Development

On-demand, app-based ride services are most commonly referred to as Transportation Network Companies (TNCs), but they also have many other names--real-time ridesharing, parataxis, ridematching, on-demand rides, ridesourcing, or app-based rides (Rayle et al. (2014)). The California Public Utilities Commission (CPUC)'s definition of a TNC is "an online-enabled platform [that] connect[s] passengers with drivers using their personal, non-commercial vehicle." For now, the two features distinguish a TNC from other services. This was not always the case when they first started.

Kauffman (2018) tells a nice history of TNC's founding and development-- The first true shared-ride service was Sidecar. The Sidecar app, developed in San Francisco, enabled carpooling or drivers to share the ride (and cost) with other people who are on their way. An unintended consequence of Sidecar is that people started using it to make a profit, driving places solely so they could give other people rides and be compensated. Uber, which launched just a few years earlier than Sidecar, also had an online-enabled platform, but was exclusively a black-car-only service with towncars and limousines. Similar to Sidecar, Zimride, enabled city-to-city ride-sharing using Facebook. People driving from one city to another (i.e. San Francisco to Portland) could share the ride by selling the empty seats on Facebook. A hackaton hosted by Zimride birthed an app called Lyft, which was very similar to what Sidecar was at the time. The Lyft app lets ordinary people drive passengers using their own personal cars in exchange for fares. The app was not developed for carpooling or ridesharing like Sidecar, yet it continued to

use the name “rideshare”. Sidecar and Lyft were doing similar functions and competing with one another, but Lyft was “better funded and more operationally capable.” Uber later joined the competition by launching a similar type of service, which they called “UberX;” this became what we know today as the standard Uber service.

Today, Uber and Lyft continue to be major players in the TNC market, while Sidecar closed its doors in 2015 (Kelly (2015)). In addition to Uber and Lyft, other companies that provide this service include Via, Gett/Juno (in the U.S., U.K., Russia, and Israel), Ola (in India), Grab and Go-Jek (in Southeast Asia), and Didi Chuxing (in China) (Yuniar (2018), Campbell (2017) and Bosa (2017)).

The definition of TNC continues to evolve as other services attempt to adapt the same technology and as TNCs transition to owning their own personal fleet of vehicles. An example of one of those services is taxis. Apps such as Curb and Flywheel allow taxis to be more like TNCs by contracting the application which includes GPS and an online payment system (Evans (2017) and Yeung (2017)). Taxi companies that do not want to contract the technology often develop their own application, but their “cab infrastructure [sometimes is not standard and] varies wildly between cities” (AskMetaFilter (2015)). Some transit agencies also incorporate similar technologies. For example, San Francisco (SF) Municipal Transportation Agency (SFMTA) uses SF Nextbus, a mobile phone app and online platform that provides live location and estimated wait times of their bus and rail services in San Francisco (NextBus). Meanwhile, MuniMobile, allows passengers to purchase tickets using their mobile devices (MuniMobile). TNCs are also moving towards owning their own fleet of vehicles. While they are often criticized for not bearing the costs of vehicle maintenance, insurance, and depreciation because most do not own their own fleet of vehicles (Jones (2018)), some TNCs do own vehicles. In such places as

Singapore, where car ownership is very expensive and limited to only a number of people, the TNCs have to own some vehicles to be leased out to drivers (Lin (2017)). Furthermore, virtually all TNCs are racing to achieving their own sustaining fleet of autonomous vehicles (Jawkins (2018))

Another distinguishing characteristic of a TNC is that it is usually door-to-door, or they pick-up and deliver passengers at their specified locations. Via, however, acts more like a flexible, on-demand transit since it allows ride-sharing and picks up and delivers passengers by zones (Whiney (2016)). Pick-up and delivery by zones means that customers must walk minimally (no more than a couple of blocks) from their origin to their pick-up location or from their drop-off location to their destination.

2.2 TNC Service Characteristics and Impacts on Access and Equity

Several studies have investigated TNC wait times, ride times, and fares before comparing them with those of taxis or for different TNC customers.

One of these, Rayle et al. (2014), conducted a survey of about 380 TNC users in San Francisco and inquired about passenger wait times. According to their findings, TNC wait times relative to taxi dispatch times were much shorter (data on taxi dispatch times were taken from the San Francisco Municipal Transportation Agency, logs by a taxi company in San Francisco, and the American Community Survey). For example, about 90% of TNC respondents said they waited ten minutes or less, during the day or night and on a week day or weekend. 67% waited five minutes or less. In contrast, only about 35% of passengers who were picked-up by a taxi, had wait times of less than ten minutes (during the day and weekday). Those who were picked up by taxi during the night and weekends with less than a ten-minute wait time were even fewer—about 16% of passengers. Another study, Smart et al. (2015), deployed riders in low income

neighborhoods in Los Angeles and instructed participants to take a taxi or UberX. After controlling for the same ride (same origin and destination pairs and time-of-day), they found the average wait times of taxis to be two to three times longer than that of UberX, even though they (the taxis) cost more. Also based on their findings, on average, a taxi ride costs $14.63, while a TNC ride is about half or $6.40. With shorter wait times and lower fares, the study suggests that TNC may be increasing access, especially for minorities living in low-income neighborhoods. Goldman and Liu (2015) had consistent results. They estimate TNC and taxi fares using each service's publicly posted rates (formulas which are functions of distance, surge pricing, and pick-up locations). Their estimated TNC fares (Uber, Lyft, Sidecar) are almost always lower than their estimated private taxi fares, whether during weekdays, weekends, and even dynamic pricing periods.

Ge et al. (2016) and Hughes and MacKenzie (2016) compared TNC characteristics for different customers. Ge et al. (2016) sent passengers in Seattle, WA and Boston, MA to ride TNCs and collected key metrics such as wait times, ride times, and cancellation rates of nearly 1,500 rides. Their results showed disparities in the number of cancelled requests, wait times, and ratings by drivers for TNC customers with different racial names or profile pictures. Those with African American sounding names compared to white sounding names tend to experience longer wait times (by as much as 35%) and more frequent cancelations (twice as likely in high density areas and three times as likely in low density areas). Ride times also seem to vary for customers of different genders. In Boston, the same rides for female customers as opposed to male customers tend to be longer and more expensive. Hughes and MacKenzie (2016) explored TNC wait times, particularly those of UberX in the greater Seattle area. Their data is from the Uber Application Programming Interface and over the course of two months in 2015. They did not

find longer wait times for customers not in “white and wealthy” areas. They did find higher TNC performance in dense urban areas.

2.3 Demand for TNC and Impacts on Vehicle-Miles-Traveled and Congestion

Some studies examine the growing demand for TNCs and their effects on vehicle-miles-traveled (VMT) and congestion. While most of these observed rapid growths in the demand for TNC services, there does not seem to be consensus regarding whether in aggregate, TNCs add or abate existing high levels of traffic congestion and VMT.

Rayle et al. (2014) suggest that most modal shifts to TNCs come from taxis and buses, while some users were using Uber or Lyft as a first/last mile service to go to or from the transit stations. According to their survey, 39% of the TNC users would have taken the taxi if TNCs were not available, whereas 24% would have taken the bus. Moreover, four percent of users either got picked up or dropped off at a public transit station while the average distance of TNC trips were about 3.1 miles. Presumably, these riders were using TNCs to reach public transit stations that may a bit too far for walking. 40% of TNC users also reported that they reduced their driving since TNCs became available.

Another paper, Clewlow and Mishra (2017), examined data from a travel and residential survey that was conducted in seven major U.S. cities. Based on their analysis of TNC’s negative and positive impacts on VMT, they believe in net, TNCs result in increased VMT. They claim most TNC users did not change their travel behavior with regards to driving (car ownership or personal driving), but 9% reported disposing their personal vehicle and 26% reported reducing driving their personal car. Additionally, the paper found that TNC was affecting different kinds of transit disparately. While it increased the use of commuter rail service, it lowered the use of

bus and light rail service. TNCs also reduced biking, but increased walking. Finally, 49-61% of TNC trips would not have been made at all if their service did not exist.

Similarly, Schaller (2017) believes that TNCs are "unsustainable," because they heighten traffic congestion in New York City (NYC). They analyzed electronic trip logs of TNCs and taxis, other trip logs of for-hire vehicles (taxis, limousines, and TNCs) from the Taxi and Limousine Commission (TLC), monthly taxi trip volumes data, current licenses, and vehicle mileage data in NYC. They found ride services (yellow and green cabs, and for-hire vehicles including TNCs) rose each year in 2012-2016, while subway and bus ridership dropped significantly each year, in the four consecutive years. Even after accounting for the drops in mileage from taxis, black cars and car services, from personal vehicle use by some TNC drivers and passengers, as well as from some TNC passengers who "pooled" or shared the ride with other passengers, they estimate the net increase in driving from TNCs to be about 600 million miles from 2013-2016.

Contrary to previous results, researchers at the Massachusetts Institute of Technology's Computer Science and Artificial Intelligence Laboratory see great potential in shared rides, especially that by pooled TNC services such as Uber Pool or Lyft Line. According to their research (Alonso-Mora et al. (2017)), these services leveraged the technology to improve for-hire services. With the help of GPS and optimization tools, they can run more efficiently than taxis and reduce the number of for-hire vehicles on the road by 75% without significantly impacting travel time (Conner-Simons (2016)). They claim that with the right application, "95 percent of demand would be covered by just 2,000 ten-person vehicles, compared to the nearly 14,000 taxis that currently operate in New York City."

2.4 TNC Services and Impacts at Airports

Studies specifically on the demand for TNCs and their impacts at the airport are more limited. SFO (2017), Mandle and Box (2017), and Mandle and Box (2016) analyzed the growing demand for TNCs and how much it is replacing all other modes to the airport. SFO (2017) examined the rise in TNC trips at SFO. Based on the monthly number of TNC trips from October 2014- July 2017, TNCs account for 19% of all commercial ground transportation trips (or 100,000 trips) in October 2014 and 71% (or 700,000 trips) in July 2017 (SFO (2017)). Mandle and Box (2017) and Mandle and Box (2016) surveyed airport staff members responsible for ground transportation operations at 100 of the largest US airports during Fall 2016. Responses from 72 of the airports gave insights to how TNC's demand is substituting other modes and how those shifts affect airport revenues. Based on airports where TNCs had been operating for at least a year, 61% of airports saw a decrease in taxicab revenues and no change in limousine revenues. Additionally, 57% of airports saw a decline in shared-ride van revenues, while 48% saw no change in rental car revenue. Furthermore, some airports witnessed significant passenger shifts from being dropped-off to now taking TNCs; when this happens, the airports receive a new stream of revenues from the airport fees that they charge TNC users. Finally, survey responses also show about a 5% to 10% decline in the number of parking transactions per airline passenger. According to Walker Consultants (2017), parking revenues remain stable despite uptakes in the number of TNC rides and dips in the demand for parking; they claim many airports raised parking rates to try to recover from the loss in demand.

2.5 Airport Access Mode Choices

Statistical studies of ground transportation to airports date back to at least the early 1970s. Ellis et al. (1974) and Leake and Underwood (1977) were among the first papers to look at

access mode choices for transportation to the airport using simple multinomial logit models. As is well known, a major limitation of the multinomial logit model is that it assumes independence of irrelevant alternatives (IIA - alternatives are not correlated through random disturbances) meaning that the ratio of two alternatives' probabilities is independent of the presence of the other alternatives. As it turns out, this assumption is not valid for many mode choice studies because some modes share common unobserved attributes.

Current research on surface transportation and modal choice has progressed to employing more complex generalized extreme value models, including nested logit models, in order to address this concern. Nested logit modal choice models are commonly used in airport ground access studies, usually nesting private modes such as automobiles separately from public or shared modes such as rail and buses. Recent work on airport ground transportation, including Tam et al. (2011), Akar (2013), Psaraki and Abacoumkin (2002), Alhussein (2011), all use multinomial logit models, while others, including Pels et al. (2003), Cirrilo and Xu (2010), and Gupta et al. (2008), use nested logit to analyze airport ground passenger data. Alternatively, Manzano (2010) and Tsamboulas and Nikoleris (2008) relied on related discrete choice probit models to estimate travel demand to airports. On a more theoretical choice level, the elimination by aspect model of decision making (Tversky (1972)), a model where, in stages, alternatives are viewed and evaluated as a set of aspects, has not been applied within an airport access mode choice setting. However, the latter has been used to analyze the demand for urban rail in Tokyo (Kato and Kosuda (2008)).

Pels et al. (2003) analyzed not only ground transportation modes to the airport but also airport choice in the multi-airport Bay Area region in California. They found that access time plays a major role in airport choice decisions and confirmed that business passengers have a

higher value of time, higher access time elasticity, and lower cost elasticity than do leisure passengers.

This dissertation (chapter five) is the first to analyze ground transportation mode choices while focusing on TNCs as one of the alternatives. All of the previously mentioned literature on airport access mode choice did not include TNC.

2.6 Pick-Up and Delivery Problem and Its Application to Airport Access Requests

While there are numerous studies on the pick-up and delivery problem (PDP) to more efficiently route the transport of goods (for example Wang and Regan (2002) and Yang et al. (2002)) or of passengers in Dial-A-Ride, shared ride service settings (such as Psaraftis (1983), Masoud (2016), Wong and Bell (2006), Jaw et al. (1986), Vodopivec et al. (2015), Do et al. (2018), Wang et al. (2018), Diana and Dessouky (2004), Atasoy et al. (2015), Madsen et al. (1995), Dumas et al. (1991), Cordeau and Laporte (2003), and Cordeau and Laporte (2007)), few (including Feng et al. (2017) and Tang et al. (2015)) have applied it to airport shared ride services. Psaraftis (1983) describes the exact solution method while the others (Wong and Bell (2006), Jaw et al. (1986), Vodopivec et al. (2015), Do et al. (2018), Wang et al. (2018), Diana and Dessouky (2004), Atasoy et al. (2015), Madsen et al. (1995), Dumas et al. (1991), and Cordeau and Laporte (2003)) solve the problem with real data and employ heuristics based on insertion methods or tabu search, which is common when solving large scale, NP-hard problems. Cordeau and Laporte (2007) is a meta study of the Dial-A-Ride Problem (DARP) and summarizes the important and distinctive features of various DARP versions and algorithms. Feng et al. (2017) refers to the problem as the Airport Access Ridesharing Problem (AARP). They formulated the AARP as a mixed integer program. Meanwhile, Tang et al. (2015) calls it

the Multi-Trip Mode (MTM) of Door-to-Door service of Pickup and Delivery of Customers to the Airport (D2PDCA) Problem.

In Feng et al. (2017), three operational policies for airport shuttles are explored. The first policy optimizes requests of departing passengers going to the airport (inbound) and arriving passengers leaving the airport (outbound) separately. The second policy optimizes inbound and outbound requests simultaneously. Finally, the third policy prioritizes outbound requests, which make up the majority of their customers, by adding some constraints to ensure that all pick-ups of inbound passengers are conducted after all outbound passengers have been delivered. They applied the problem to actual airport shuttle requests for one service day in January of 2012 at Washington Dulles International Airport. The problem consists of 164 outbound requests and 22 inbound requests. Costs or travel time between origin and destination pairs were calculated using the Network Analyst toolbox of ArcGIS (function to build and perform analyses on a network data set). The vehicles are homogeneous and have the same capacities. Unable to find an exact solution for all the 186 requests, they then solved the problem using a subset of the customers (10, 20, and 30 requests). They compared the algorithm performance (total system cost and computational times) under the different policies and using the exact solution method vs. the heuristic approaches (sequential insertion procedure (Jaw's Heuristic) or insertion I1 procedure (Solomon's InsertionI1Heuristic)).

In Tang et al. (2015), the objective is to quantify the cost savings under MTM compared to the single-trip mode. The MTM allows vehicles to conduct pickups following deliveries at the airport, whereas the single-trip mode restricts direct returns to the depot. It uses an exact algorithm based on the trip-chain-oriented set-partitioning (TCO-SP) model. The exact algorithm includes a label-correcting method that excludes infeasible trip chains to shorten search process.

Chapter 3

Availability of Various Types of TNC Services at Airports

3.1 Introduction

While studies of on-demand, app-based ride services or Transportation Network Companies (TNC) are widely available, those on TNCs at airports are limited. Thus, not much is fully understood about the demand for TNCs to and from the airports. Studies are beginning to answer some of these questions: how fast is the growth of TNC rides at airports? How do they influence other ground transportation modes? This chapter explores related questions regarding TNCs at airports, mainly, which airports permit TNCs and what types of services do the TNCs provide. There are many TNCs, but it is primarily focused on the leading TNCs, Uber and Lyft. The analysis provides insights to the scale and opportunities of TNC operations at airports in the U.S. and around the world.

TNC operations at airports in the U.S. and worldwide are extensive. Most of the literature (SFO (2017), Hermawan and Regan (2018), Mandle and Box (2017), and Mandle and Box (2016)) that evaluated TNC's effects on all other modes are based on data from San Francisco International Airport (SFO). SFO was the first airport in the U.S. and one of the first in the world, to develop permit agreements with TNCs; one of the terms of their agreements is that TNCs must report and provide data of all their operations on SFO airport grounds (SFO (2017)) and the airport authority makes the data publicly available. We first aim to understand where

TNCs operate in the U.S. and worldwide, so that we can begin to accumulate and analyze data at the other airports.

Some TNC services aim to address the issues related to lack of access, low vehicle-occupancy, and emissions. (Hermawan and Regan (2017)) estimates travel times and costs from many locations in Southern California to Los Angeles International Airport (LAX) by all modes. They found that on average, standard TNC was the least expensive private mode, with fares that are only about 55% that of taxis. This chapter identifies the number of airports with and without standard TNC service (uberX, uberPOP, or Lyft). For example, some airports only have TNC services that are more similar to taxis (uberTAXI or uberBLACK), which have professional/commercial drivers and cost as much as taxis, and some airports do not have any TNC services at all. Then, it investigates the number of airports with the following TNC services: uberPOOL or Lyft Line (where they match two small parties in the same ride), uberGREEN (where the vehicle is electric), and uberASSIST (where the driver can help riders into vehicles and accommodate with folding wheelchairs, walkers, or scooters).

While Hermawan and Regan (2017), Mandle and Box (2017), and Walker Consultants (2017) are the first studies showing TNC operations at multiple airports in the U.S., this chapter adds to the literature by identifying all airports where major TNCs operate nationally and globally. In addition to exploring which airports, it also documents the type of TNC services provided.

3.2 Data and Methodology

TNCs seldom make data on their operations and trips available to the public. They are only beginning to report and provide data to the airports. As a result, past and current airport studies typically rely on survey data collected by the airports themselves (e.g., Passenger Survey

and Customer Survey) or by consulting groups such as InterVISTAS Consulting (e.g., electronic airports' staff survey). Uber was founded in 2009 and Lyft in 2012, but the airports did not collect data on TNCs until several years later. For example, 2015 was the first year in which LAX included TNCs as one of the access modes in the LAX Airport Passenger Survey.

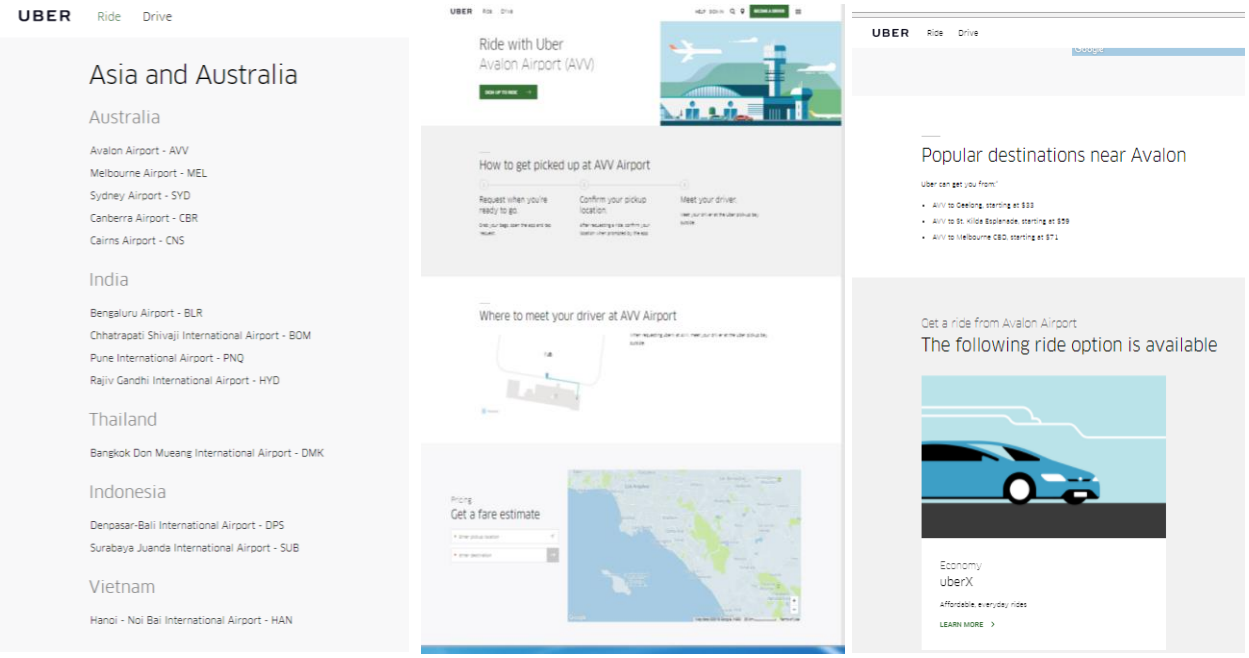


Figure 3.1. TNC Information at Airports from Uber Website

This study collects data published on the Uber and Lyft websites (last accessed on February 7, 2018). Examples of the sites (from Uber) are shown above (Fig. 3.1). These data provide the following information: exhaustive list of all the airports they serve, and for each airport, the name of the airport, steps to ride (i.e. meet driver at departure level), estimated fares to main locations (i.e. downtown areas), and the type of rides available. The data do not contain personal information of riders or individual trips. It compiles TNC information at each airport from 271 airports (Uber) and 321 airports (Lyft). It then geocodes the airport locations using Google Maps API and maps the coordinates (latitude and longitude) using ArcGIS.

Additionally, it uses the Global Airport Database, which has information on 9,300 large and small airports worldwide (a large but not exhaustive list of airports). The data include the ICAO and IATA codes, the country and city, the latitude-longitude coordinates, and the altitude above mean sea level of the airports.

3.3 Coverage Areas of TNC at Airports

Table 3.1. TNC Service at Airports (Number of Airports)

Summary	Uber	Lyft	Uber Only, Lyft Only, or Both Uber and Lyft
Total	271	321	462
Common	130	130	-
US	146	313	330
Outside of US	125	8	127

The number of airports with TNC service are summarized in Table 3.1 above. In total, Uber serves 271 airports worldwide, and Lyft serves 321 airports worldwide. A total of 130 airports have both Uber and Lyft, which means that TNCs (either only Uber, only Lyft, or both Uber and Lyft) are in 462 airports. Compared to Lyft, Uber serves fewer than half the number of airports in the U.S. It is in 146 airports, whereas Lyft is in 313 airports. Outside of the U.S., Uber operates in 125 airports (in more than 40 different countries), while Lyft is in eight airports (exclusively in Canada). Lyft does not have airport operations outside of North America, but it directs its users traveling abroad to download their partners' apps (Didi in China, Ola in India, and Grab in Southeast Asia) (Bosa (2017)). Because of the extensiveness of TNC operations at many and heterogeneous airports (small, medium, and large airports, and at airports with and without competing TNC services), there is a need to collect and analyze data on their market share and impacts at various airports.

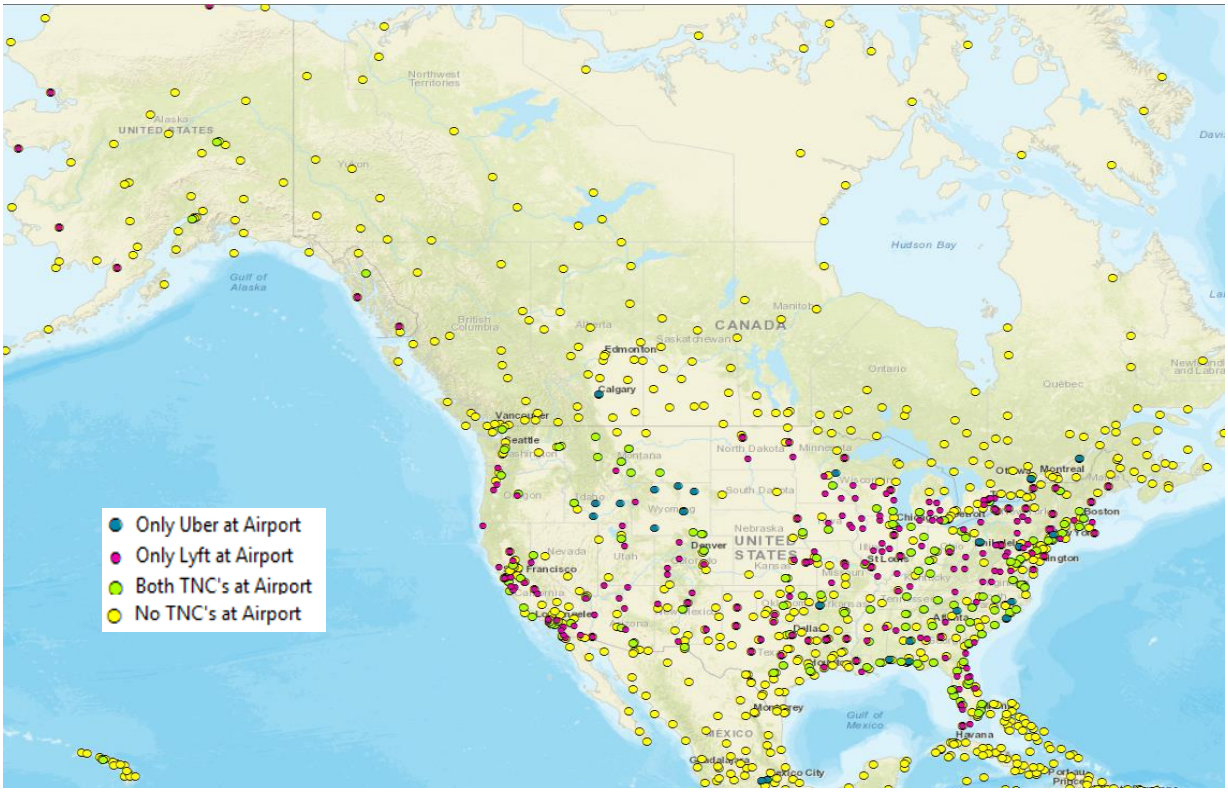


Figure 3.2. U.S. Airports with Uber, Lyft, both TNC, and No TNC Service

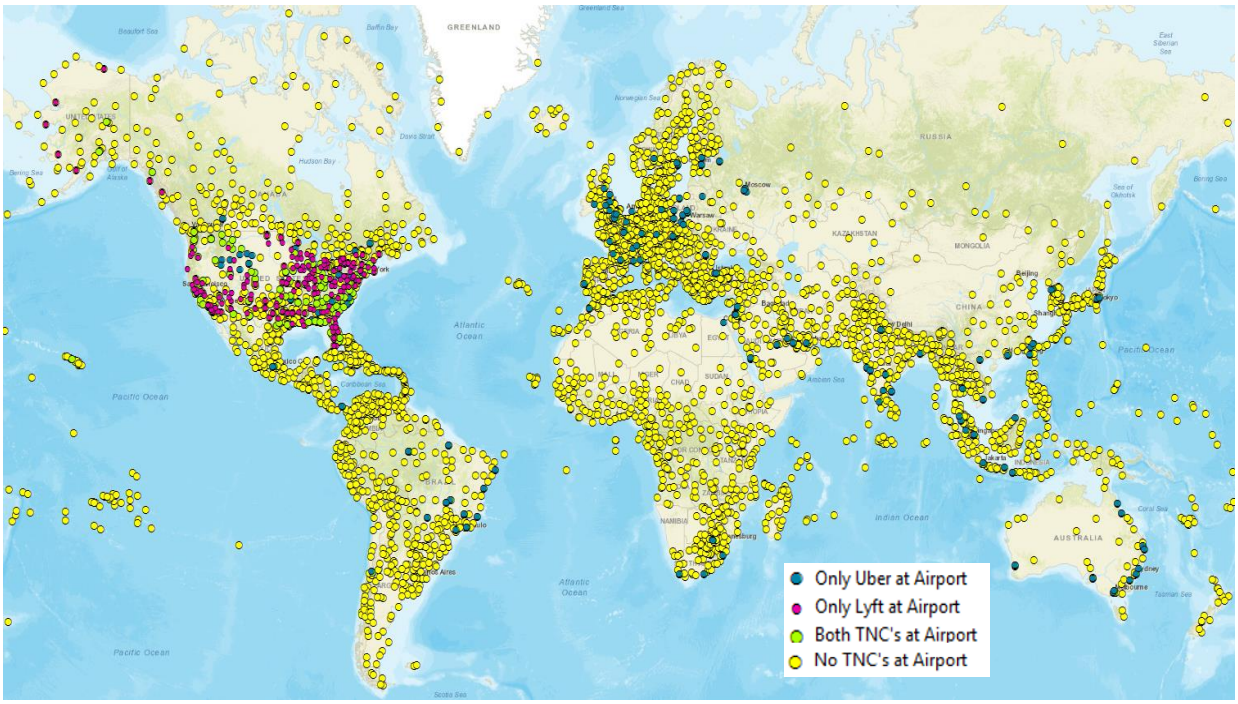


Figure 3.3. Worldwide Airports with Lyft, Uber, and No TNC Service

Figures 3.2 and 3.3 (above), show US and worldwide airports with only Uber service, only Lyft service, both TNC services, or no TNC services. The 330 U.S. airports with TNCs are widely dispersed, including in Alaska and Hawaii. Few states (such as South Dakota) do not have TNCs at the airports. Several airports in Idaho and Wyoming only had Uber and no Lyft, and a number of airports spread across the country only had Lyft and no Uber.

Unlike Lyft, which serves airports only in the U.S. and Canada, Uber is at airports in 43 different countries worldwide. Passengers can hail an Uber at airports in such countries as: Mexico, Panama, Brazil, Chile, South Africa, Ireland, UK, Germany, Poland, Portugal, Romania, France, Norway, Sweden, Finland, Turkey, Egypt, Lebanon, Israel, Saudi Arabia, U.A.E, India, Bangkok, Vietnam, Indonesia, Singapore, Taiwan, Hong Kong, Japan, and Australia. Countries without Uber services at their airports include: Guatemala, Nicaragua, Costa Rica, Cuba, Colombia, Ecuador, Peru, Argentina, Bolivia, Iceland, Spain, Italy, Greece, Iran, Cambodia, and the Philippines.

3.4 TNC Service Types at Airports

Several types of TNC service at airports (standard, pooled, alternative fuel vehicles, and with drivers who accommodate riders with disabilities) are explored and summarized in Table 3.2. Most airports with TNC service have the standard service. These are the everyday, affordable, private rides for up to four people. They are usually in sedans and they rely on freelance, non-professional or non-commercially licensed drivers. Only 12 airports where Uber operates (about 4% of airports) do not have the standard Uber service (uberX and uberPOP), while 13 airports where Lyft operates (also about 4% of airports) do not have standard Lyft service (Lyft). Meanwhile, there are 38 airports (8% of all airports where they operate) with pooled Uber and Lyft services (these include only uberPOOL, only Lyft Line, and both

uberPOOL and Lyft Line). Pooled TNCs are door-to-door and match separate, small parties (up to two riders in each party) going in the same direction in the same ride. Because costs are also shared, they cost less than standard TNCs. Even more limited are the number of airports with TNCs that advertise their use of alternative fuel/ electric vehicles (uberGREEN), at only about three airports. Finally, the number of airports with TNC service that accommodates passengers with disabilities (uberWAV and uberASSIST) is 25 (or about 9% of all airports where Uber operates). Both offer additional assistance to senior or passengers with disabilities. UberASSIST helps with the folding of wheelchairs, walkers, and collapsible scooters, and uberWAV has wheelchair-accessible ramps or lifts. With the variety of services that they offer, TNCs aim to fill the gap in affordable, high vehicle-occupancy, low-emissions, and paratransit rides. However, with the exception of standard TNC services, those that are pooled, with alternative fuel, or with paratransit are at fewer than 10% of the airports where they serve.

Table 3.2. Type of TNC Service at Airports (Number of Airports and Percent)

Service	Uber	Lyft	Uber Only, Lyft Only, or Both
Standard (uberX, uberPOP, Lyft)	259 (96%)	308 (96%)	445 (96%)
Pooled (uberPOOL, Lyft Line)	21 (8%)	32 (10%)	38 (8%)
Alternative Fuel (uberGREEN)	3 (1%)	-	-
Paratransit (uberWAV and uberASSIST)	25 (9%)	-	-

Other types of Uber and Lyft services at airports are listed in Table 3.3. Uber has 47 different types of services, while Lyft offers six different kinds of services. Some of the distinctions are by different capacities (uberXL and Lyft Plus can seat up to six passengers, uberXXL can seat up to 16 passengers), classes (Premium, UberLUX, Lyft Lux are high-end), with drivers who speak certain languages (uberESPANOL, UberMANDARIN, and uberEnglish), with professional drivers (uberVAN, uberEXEC, uberBERLINE, and uberPREMIUM), and taxi equivalents (uberTAXI and uberTAXIVAN).

Table 3.3. Uber and Lyft Service Types

Uber				Lyft
7 Seater	uberFLASH	UberSELECTXL	uberXL	Lyft
CAR SEAT	uberGO	uberSKI	UberXXL	Lyft Line
Child Seat	uberGREEN	uberSKISELECT		Lyft Lux
Premium	UberLUX	UberSUV		Lyft Lux SUV
Premium SUV	UberLUXSUV	uberTAXI		Lyft Plus
SUV	UberLUXXL	uberTAXIVAN		Lyft Premier
Uber Car Seat	UberMANDARIN	UberTRIP		
uberASSIST	uberMOTO	UberVAN		
UberBAG	uberMOTOR	UberVAN+CarSeat		
UberBERLINE	uberNIGHT	uberWAV		
UberBLACK	uberPOOL	uberWINE		
uberEnglish	uberPOP	uberWINEXL		
uberESPANOL	UberPREMIUM	uberX		
UberEXEC	UberPREMIUM SUV	uberX VIP		
UberEXECLARGE	UberSELECT	uberXBAG		

3.5 Conclusion

This chapter shows the number of airports with TNCs and the different types of services they provide. TNCs are in 462 airports worldwide. Lyft operations at airports are exclusively in the U.S. and Canada, but Ubers are at 146 airports in the U.S. and 125 airports in over 40 countries outside of the U.S. Additionally, there are almost 50 different kinds of Uber services and six kinds of Lyft services at airports. Some of these services provide affordable, high vehicle-occupancy, low-emission, and paratransit rides. They are called uberX, uberPOP, Lyft, uberPOOL, Lyft Line, uberGREEN, uberWAV and uberASSIST. While standard TNCs (uberX, uberPOP, and Lyft) are mainstream, the other services are available only at fewer than 10% of the airports where they serve.

Chapter 4

TNC's Impacts on the Use of Shared Modes, Vehicle-Occupancy, and Curb Congestion at Airports

4.1 Introduction

Congestion at airport terminals has tremendous negative impacts on airport patrons and the surrounding communities; perhaps the most familiar and direct impact is the rise in passenger disutility resulting from the need to arrive early to prevent catastrophic schedule delays, or the impacts of those delays when passengers elect not to add in a buffer and then miss their flights. Other effects include increases in opportunity costs and in fuel consumption and pollution. Not only does congestion have adverse effects, it also is prevalent at many airports. Los Angeles International Airport (LAX) for example, experiences severe congestion. "… the upper level curbside demand exceeds the available curbside length during the peak hour by about 60 percent, while the lower level demand exceeds capacity by nearly 50 percent." (LAX Economic Impact Review (2009)).

With the advent of Uber and Lyft at airports, a major concern is that these on-demand, app-based ride services, which are mostly private-use instead of pooled-use, will increase traffic. TNC operations at airports are highly controversial. For example, Uber and Lyft, founded in 2009 and 2012, respectively, could only recently pick up passengers at Los Angeles International Airport starting in January 2016; at Long Beach Airport, it was even later, in April 2017. This chapter analyzes TNC's impacts on shared mode use, vehicle-occupancy and curb congestion at airports. Data from the 2015 passenger survey from LAX, San Francisco International Airport (SFO), and Oakland International Airport (OAK) provided information on the share of pooled

vs. standard TNC services, as well as how much they are they replacing and complementing shared vehicles (shared vehicles are public transit such as buses and light rail, shared or vans or shuttles, which typically have higher vehicle-occupancy). The objective is that by understanding these relationships, one can also set some modal shift targets (shifts to vehicles with higher occupancy) and reduce congestion.

4.2 Data and Methodology

The data are from the 2015 LAX Passenger Survey Dataset and the 2015 SFO-OAK Customer Survey Dataset. In the study, the focus is exclusively on passengers departing from, and not connecting at, LAX, SFO, or OAK. The 2020 projections are also based on 2014, 2015, and 2016 SFO Customer Survey Dataset.

2015 LAX Passenger Survey

The 2015 LAX passenger survey is a one-on-one survey administered using electronic tablets at LAX boarding gates. It was commissioned by Los Angeles World Airports and is typically conducted every five years. The 2015 and 2011 LAX passenger surveys were carried out by Unison Consulting, Inc. With nearly 100 multiple choice and open-ended questions, the survey is extensive. Among the many questions, the survey inquired if the departing passenger(s) is (are) traveling for business or for leisure, the duration of the trip, and his or her primary mode of transportation to the airport. Based on the responses, there were different follow-up questions. For example, respondents who specified that their primary form of transportation was a private vehicle were asked more specific questions regarding their chosen mode of ground transportation, such as whether they were dropped off, parked at the airport, or parked off site, and how many people were in the same vehicle. Both visiting and Southern California residents, who are originating or connecting at LAX, were interviewed over the course of two

nonconsecutive weeks, in April 13-19 and in July 13-19, 2015; over 13,400 survey responses were collected. The 2015 survey was the first time that TNC was included as an alternative mode.

2015 SFO-OAK Passenger Survey

In the 2015 SFO-OAK Passenger Survey, different departing passengers (who are either originating or connecting) were interviewed every month in May 2014-May 2015 and asked over 100 questions. The survey was administered at Oakland International Airport and San Francisco International Airport, either by tablet, paper, or online, and its sample size is over 27,000 travel parties. Many of the questions were similar to that in the LAX survey; for example, they asked the passenger's primary mode to the airport and those using private modes, how many people in the travel party were in the same vehicle. In contrast to the LAX survey, here they asked several in-depth questions related to TNCs. Some of those questions include the name of the TNC service that they took (Uber, Lyft, Sidecar, Uber Pool, and so on), the preferred airport access mode prior to TNC service, and whether they used TNCs to get to the station if they took the bus, train, or rail service.

2014-2016 SFO Customer Survey

These customer surveys are administered annually at SFO at the boarding gates, by mail, or on-line. They include both passengers originating and connecting at SFO. The surveys share many common questions to those in the LAX and SFO-OAK surveys. For example, the customer surveys inquired about the passenger's primary mode to the airport, with TNCs as an alternative. Another shared question is for those who drove a private vehicle, where one parked. In contrast to the other surveys, it does not ask much further about TNCs or about access modes. It also provides the data in different years. The sample size is about 3,000 individuals for each year.

4.3 TNC's Effects on the Already High Use of Private (Typically Lower Occupancy) Modes

One of the leading causes of congestion at airports is the high use of private modes, which tend to be much lower in vehicle-occupancy. Since missing a flight can be very costly to air travelers, most of them prefer private modes because they are much faster and more reliable. Data from the 2015 LAX Passenger Survey and the 2015 SFO and OAK Passenger Survey, suggest that this is true at LAX, SFO, and OAK. Here private modes include passenger cars, taxis, limousines, private TNC rides, and private vans and shuttles. Shared modes are public transit such as buses and light rail, shared vans or shuttles, hotel courtesy shuttles, and rental cars (passengers use shared shuttles because rentals are returned or picked up off-site).

At least half of the departing passengers at LAX, SFO, and OAK fly alone. Table 4.1 (below) lists how they travel to the airport. 78%, 63%, and 70% used private modes at LAX, SFO, and OAK respectively. Bay Area airports have slightly fewer solo travelers who used a private mode compared to LAX. It may be because shared modes (including rail and other public transit services) there are more extensive and thus more convenient to use relative to that in Los Angeles.

Table 4.1. Of Passengers Flying Alone, Use of Private vs. Shared Modes, 2015

Mode	**LAX**	**SFO**	**OAK**
Private	78%	63%	70%
Shared	22%	37%	30%

Table 4.2 (below) shows vehicle occupancy by private modes. In the LAX survey, passengers were asked how many people (including themselves) were in vehicle, and this might have resulted in respondents including their drivers as well. Assuming that drivers were also counted, nearly 71% of private vehicle users at LAX had no more than two passengers in the vehicle. At SFO and OAK, they were asked how many people in their travel party came in the

same vehicle. If presumably drivers (not in the travel party) were excluded, almost 90% of private vehicle users there had no more than two passengers in the vehicle.

Table 4.2. Vehicle-Occupancy at LAX, SFO, and OAK Airport by Private Vehicles, 2015

	LAX			SFO			OAK		
No. of People in Vehicle	**Freq.**	**Percent**	**Cum.**	**Freq.**	**Percent**	**Cum.**	**Freq.**	**Percent**	**Cum.**
1	734	12.63	12.63	7,362	67.27	67.27	4,309	67.25	67.25
2	2,032	34.96	47.59	2,413	22.05	89.32	1,431	22.33	89.59
3	1,345	23.14	70.73	562	5.14	94.45	335	5.23	94.82
4	696	11.98	82.71	371	3.39	97.84	182	2.84	97.66
5	420	7.23	89.93	100	0.91	98.76	75	1.17	98.83
6 or more	585	10.07	100	136	1.24	100	75	1.17	100

Currently, TNCs can operate at various airports, including SFO and OAK. Tables 4.3 and 4.4 provide some insights on how the inception of TNC services at airports affects the use of private vs. shared modes there. At SFO and OAK, respectively 21% and 29% of air passengers who arrived at the airport by TNCs claim to have substituted from shared modes. Meanwhile, the share of TNC users are 8% and 3% at the SFO and OAK airports respectively. This means that about 1.7% and 0.9 % of all departing passengers at the respective airports shifted from vehicles with traditionally higher occupancy to TNC. Most modal shift to TNC from shared modes at the two airports comes from the Bay Area Rapid Transit (BART), which is the regional rail service in the San Francisco Bay Area. 15% and 21% of current TNC users at the respective airports typically used BART to go to the airport before TNCs were available (or 1.2% and 0.63% of all departing passengers at the respective airports). On the other hand, among shifts from all modes, many passengers claim to have switched from taxis.

Table 4.3. Of Passengers Arriving by TNC, Preferred Mode to SFO and OAK Prior to TNCs, 2015

		SFO			OAK		
Mode	**Shared?**	**Freq.**	**Percent**	**Cum.**	**Freq.**	**Percent**	**Cum.**
BART	Yes	215	14.91	14.91	51	20.56	20.56
Bus	Yes	15	1.04	15.95	1	0.4	20.96
Shared Vans/ Shuttles	Yes	46	3.19	19.14	8	3.23	24.19
Rental	Yes	26	1.8	20.94	13	5.24	29.43
Limousines	No	35	2.43	23.37	5	2.02	31.45
Private car	No	308	21.36	44.73	80	32.26	63.71
Taxi	No	797	55.27	100	90	36.29	100

Table 4.4. Of Passengers Arriving to SFO and OAK by BART, Chosen Mode to BART Station, 2015

SFO			OAK		
Mode	**Freq.**	**Percent**	**Mode**	**Freq.**	**Percent**
ACE	1	0.05	ACE	1	0.1
SamTrans	1	0.05	Biked	1	0.1
VTA	1	0.05	SamTrans	1	0.1
Emery Go Round	2	0.1	Golden Gate Transit	3	0.31
Caltrain	4	0.21	VTA	3	0.31
Golden Gate Transit	7	0.36	Emery Go Round	4	0.41
Amtrak	9	0.46	Country Connection	5	0.51
AC Transit	26	1.34	Caltrain	8	0.82
TNC	49	2.53	TNC	28	2.86
Taxi/Cab	53	2.73	Taxi/Cab	41	4.19
Drove and Parked	65	3.35	AC Transit	46	4.7
Muni	177	9.12	Drove and Parked	48	4.9
Dropped Off	437	22.53	Muni	57	5.82
Walked	1,108	57.11	Dropped Off	235	24
			Walked	498	50.87

Table 4.4 shows how passengers arriving to SFO or OAK by BART get to the BART station. At both airports, about 11% of all airport passengers take the BART and nearly 3% of those passengers used TNCs as a secondary mode. Thus, TNCs are complementing mass transit somewhat for a very small share of airport patrons (about 0.33%). These passengers may be just a little too far from the station and a private mode such as TNCs is perfect for their short ride to the station. The share using TNC as a secondary mode is just a little short of those using taxis as a secondary mode, which is surprising because TNCs are usually much less expensive than taxis.

Additionally, the most common secondary modes are “walk” and “dropped off”, which suggests that most people who take the BART live near the stations.

Table 4.5 (below) shows the share of departing passengers using the standard TNC services versus those who were pooled in 2015. About 77% of TNC users at SFO Airport took the standard service, while only about 3% were pooled (the rest did not specify the kind of TNC service). At OAK Airport, all took the standard service, perhaps since pooled TNC may not have been available at that airport.

Table 4.5. TNC Services: Standard vs. Pooled, 2015

Description	**SFO**	**OAK**
Standard TNCs (UberX, Lyft, Sidecar and Wingz)	76.66%	100%
Pooled TNC (Uber Pool and Lyft Line)	3.34%	0%

Table 4.6 summarizes all of the estimates in terms of the number of passengers departing from and not connecting at these airport (these estimates include the share using TNCs, the share who substituted or complemented shared modes with TNCs, and the share of standard vs. pooled TNC services). There were nearly 25 million, 20 million, and 5 million departing passengers who started their trip at LAX, SFO, and OAK, respectively. At LAX, approximately 2 million of the 25 million passengers used a TNC as a primary access mode. At SFO and OAK, it is about 1.6 million and 134 thousand passengers, respectively. Data on shifts and complementarities are only available for SFO and OAK. An estimated 340,000 and 40,000 passengers at the respective airports substituted shares modes with TNCs. These numbers are much greater than the number of passengers who complemented shares modes with TNCs, which are about 72,000 and 15,000 passengers, respectively. Again, most of the shift from shared modes to TNCs came from BART. Approximately 240,000 and 28,000 passengers at the two respective airports used to take the BART before shifting to TNCs, while those who complemented BART with TNCs are about 66,000 and 15,000 passengers, respectively. Because TNCs replace shared rides (or just BART)

more than they complement them (it), the net effect is that TNCs add to congestion as they increase the number of low-occupant vehicles at the airport. This is still true given that some passengers share TNC rides by using Uber Pool or Lyft line. Assuming that passengers who use TNCs to get to transit stations and those who use pooled TNCs are mutually exclusive, TNCs help approximately 125,000 and 15,000 passengers used shared rides at SFO and OAK, respectively (by getting them to the station or offering a pooled TNC service). These numbers are much smaller than the number of passengers who switched from shared rides to TNCs. The differences of 215,000 and 25,000 more passengers who use private modes at SFO and OAK, respectively, will result in much more additional private vehicles that will circle the airport curbside terminals.

Table 4.6. Estimated Volumes in Terms of Departing and Non-Connecting Passengers at LAX, SFO, and OAK, 2015

Description	**LAX**	**SFO**	**OAK**
Total	23,656,528	19,964,015	4,482,834
Used TNCs	1,892,522	1,597,121	134,485
Substituted shared modes with TNCs	NA	339,388	40,345
Complemented shared modes with TNCs	NA	71,740	15,069
Substituted BART with TNCs	NA	239,568	28,241
Complemented BART with TNCs	NA	65,881	14,793
Used pooled TNCs	NA	53,344	0

NA = not available

According to some reports published by the airports (Ten Year Summary of Passengers (2017), Analysis of Scheduled Airline Traffic Comparative Traffic Report (2015), and Year-end Airport Statistics Summary (2015)), the number of passengers originating at LAX, SFO, and OAK increased 6.3%, 6.3%, and 8.4 %, respectively, in 2014-2015. Meanwhile, TNC shares at SFO rose 176% in 2014-2015 and 62% in 2015-2016 (SFO Customer Survey Data (2016)).

Figure 4.1 shows the projected total number of departing passengers who started their trip at LAX, SFO, and OAK, and of those passengers, those who are expected to use TNCs, in 2015-

2020. In generating these results, it was assumed that the number of departing passengers will rise constantly each year at the rates specified above, while TNC shares will also grow, but at a slower pace each year (its growth will decelerate by about 65% each year, like in 2014-2016). It was further assumed that travel times, costs, reliability of the modes, and all other inputs of interest stay constant (ceteris paribus). The projections suggest that over 5 million passengers will take a TNC to go to LAX in 2020. At SFO, it is about 5 million passengers. While similar growth trends (in the demand for TNCs) at the two airports are expected, LAX will have more TNC users because it serves more passengers than does SFO. Of the three airports, OAK serves many fewer passengers. It also has the smallest TNC share. In 2020, about 440 thousand passengers are expected to take a TNC ride to go to OAK.

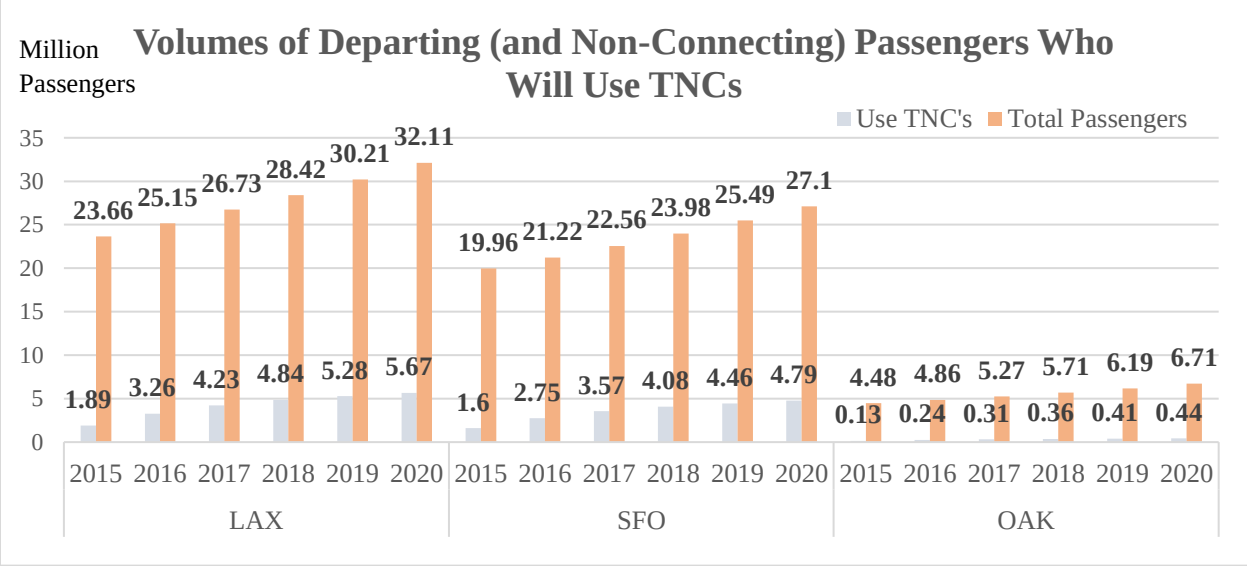


Figure 4.1. Projected Volumes of (Departing and Non-Connecting) Passengers and Those who Will Use TNCs

According to the most recent data of actual TNC use at SFO (Commercial Ground Transportation Historical Data (2017)), about 1.5 million, 2.6 million, and 1.7 million trips to the airport were by TNCs in 2015, 2016, and half of 2017 (January-June), respectively. Assuming TNCs have an average of 1.28 passengers per vehicle (SFO and OAK Passenger Survey (2015)),

there were about 1.92 million, 3.33 million and 2.17 million passengers who traveled to the airport by TNCs in 2015, 2016, and half of 2017 (January-June), respectively. The projections on Figure 4.1, which were estimated using data of TNC shares in 2015 and corrected for annual growth in passenger volumes and TNC shares, are a bit lower but still comparable to actual volumes.

Table 4.7. Projected Volumes in Terms of (Departing and Non-Connecting) Passengers

Airport	Year	Substituted shared modes with TNCs (a)	Complemented shared modes with TNCs (b)	Used Carpool Versions of TNCs (c)	Net Effects (a)- ((b)+(c))
SFO	2015	0.34	71,740	53,344	214,916
	2016	0.58	76,260	56,705	447,035
	2017	0.75	81,064	60,277	608,659
	2018	0.86	86,171	64,074	709,755
	2019	0.94	91,600	68,111	780,289
	2020	1.01	97,371	72,402	840,227
OAK	2015	0.04	15,069	0	24,931
	2016	0.07	16,335	0	53,665
	2017	0.09	17,708	0	72,292
	2018	0.11	19,195	0	90,805
	2019	0.12	20,807	0	99,193
	2020	0.13	22,555	0	107,445

Finally, this study also projects future shared modes' shifts to and complementarities with TNCs, demand for pooled TNC services, and net effects of TNCs on replacing shared rides and making shared rides possible. In these projections, which are listed on Table 4.7, it was assumed that all other shares are held constant (shares of passengers who shifted from shared modes to TNCs, shares of passengers who use shared modes, and the shares of passengers who use pooled TNC services). In 2015, TNCs increased the number of passengers who use private vehicles at SFO and OAK by about 215,000 and 25,000, respectively. In 2020, the increase in the number of passengers who use private vehicles at the two airports will be approximately 840,000 and 107,000, respectively.

4.3 Conclusion

This analysis explored the demand for TNCs, as well as TNC's relationship with shared modes (shifts and complementarities), and the demand for their shared vs. standard service at the airport. Because TNCs both replace shared rides and make them possible, it also measured the net effects at these airports. The data are from the 2015 LAX Passenger survey, the 2015 SFO-OAK Survey, and the 2014, 2015, and 2016 SFO Customer Survey. Results suggest that TNCs replace shared rides more than they complement them, and the net effect is that TNCs add to congestion as they increase the number of low-occupancy vehicles at the airport. This is still true given that some passengers share TNC rides by using Uber Pool or Lyft line. In 2015, TNCs caused 215,000 and 25,000 passengers to switch from shared to private modes at SFO and OAK, respectively. By 2020, the shift is expected to be about 840,000 and 107,000 passengers per year, respectively.

Chapter 5

TNC Market at Los Angeles International Airport (LAX)

5.1 Introduction

Approximately 37 million travelers initiated their flights from Los Angeles International Airport (LAX) in 2015 (the last year about which extensive data are available). Passengers going to the airport have a number of airport ground transportation access options, including taxi, Flyaway bus service (a regional shuttle bus service that transports passengers non-stop to and from LAX), a shared van/shuttle, a private shuttle, public transit, or most recently, on-demand, app-based ride services provided by transportation network companies (TNCs) such as Uber and Lyft. Using mobile applications, they connect passengers with drivers who provide transportation using non-commercial vehicles.

On-demand app-based rides are increasingly more prevalent at major airports like LAX. Using TNCs around Los Angeles to travel to LAX has been permitted since 2011, but initially, only pricier, commercially licensed Uber services (UberBlack and UberSUV) were permitted to pick up passengers at airport curbsides. In December 2015, Lyft became the first standard TNC service allowed to provide airport pickups at LAX, while Uber followed suit in March 2016. Because of their highly reliable, convenient, and competitively priced services (except for some notable issues arising during surge or peak demand periods), TNC services attract customers who might otherwise have chosen another mode for airport ground transportation. Despite their growing presence and demand, the characteristics and usage of TNC services at airports like LAX are still not well understood. Using Google Maps among other sources, this research

estimates and compares travel times and costs of trips in the Los Angeles area to LAX by TNCs as well as other modes of ground transportation. Then incorporating the 2015 LAX passenger survey, we also develop a model of LAX access mode choice decisions. In this light, we explore the following key questions:

- What is the current demand for TNCs for travel to LAX and how does that compare with the demand for other modes of ground transportation to the airport?
- For a number of reasons, we argue that TNCs are currently underpriced[1]. Thus, on a policy level, what would happen to the demand for TNCs if their fares were regulated and set equal to more established private modal (i.e., taxi) fares?
- Carpool versions of TNC services, such as Uber Pool and Lyft Line, that match small parties heading along similar routes are now also available in many cities, including Los Angeles. The TNCs claim that with these new options, costs can be cut by up to half while detours are no more than 10 minutes. This latter possibility raises other questions, including how will the demand for standard TNCs respond to these newer services?

There are now many stakeholders involved with TNC activity in the LAX market. To this end, many transit agencies are now partnering with or considering partnering with TNCs and taxi services to improve aspects of both their standard and paratransit operations (Swegles (2016)). Therefore, understanding regional airport access mode choice decisions should help provide insights to guide policies designed to measurably affect stakeholders with various transportation needs.

[1] TNCs fares on average are much lower than taxis. They are able to charge lower fares because they have lower operating costs (unlike taxis, they do not have fingerprint-based FBI background checks for their drivers) (Farren (2017)). With time and stricter regulations, we expect TNC fares to be more in line with that of taxis in the future.

Our extension to the existing literature is the analysis of the impact of travel time and cost on the demand for TNC rides, especially at airports. We feel that the studies we cite provide only a first step toward modeling the demand for TNC services and that additional research is needed to better understand the characteristics and policy implications of TNCs in important transportation markets.

5.2 Data and Methodology

2015 LAX Passenger Survey

The 2015 LAX passenger survey provided much of the revealed preference data used in this analysis. Commissioned by Los Angeles World Airports, this one-on-one survey is typically conducted every five years, with the 2011 and 2015 surveys conducted by Unison Consulting, Inc. Consisting of nearly 100 multiple choice and open-ended questions, the survey is extensive and is administered using electronic tablets at LAX boarding gates. Both visitors and Southern California residents were interviewed over the course of two nonconsecutive weeks, through April 13-19 and July 13-19, 2015, with over 13,400 surveys collected. The survey asks if the passenger(s) is (are) traveling for business or for leisure, the duration of the trip, and his or her primary mode of transportation to the airport. Critically for this analysis, the 2015 survey was the first time that TNC was included as an alternative mode.

Based on the resp responses, there were different follow-up questions. For example, respondents who specified that their primary form of transportation was a private vehicle were asked more specific questions regarding their chosen mode of ground transportation, such as whether they were dropped off, parked at the airport, or parked off site, and how many people in their travel party were in the same vehicle.

The data used for this research consist of travelers starting their air travel at LAX but focuses on their chosen mode of one-way access to the airport[2]. Origin and destination pairs and estimated arrival times for each passenger were extracted based, respectively, on the zip code where the traveler came from before arriving at LAX, the terminal where he or she boards, and lead time (number of hours the passenger arrives before his or her flight).

Google Maps Driving and Transit Directions

Past studies calculate travel times solely as a function of distance, but travel time depends on a variety of other factors, such as location, route, and time of day. This research uses the Google Maps Directions Application Programming Interface (API) to compute travel times for each origin destination pair. The benefits of geocoding with this method are that it allows the user to specify the location, route, and time of day of travel (via departure or arrival time) and thus is able to better map the actual transportation network.

The origin and destination pairs and estimated arrival times were entered into Google Maps to compute the distance between the origin and destination, shortest total travel time by car, and shortest total travel time by public transit. The destination was set to the exact terminal at LAX used by the survey respondent. Some observations with rare or distant origins such as Yosemite National Park or the town of Avalon (located on Catalina Island off the California coast) were excluded because Google Maps could not generate driving distance, driving duration, or transit duration for these origins. Meanwhile, other distant origins such as the city of Bakersfield generate driving directions to LAX, but there are no public transit options listed on

[2] These are one-way access trips to the airport. We assume that the access trip is independent of the egress trip, even though in some cases they are not independent. For example, some people drive to the airport because they want to have their car to drive home when they return from their air travel (egress trips).

Google Maps. These latter observations were not excluded from the sample; rather, in these cases, the option of public transit was deemed as simply unavailable to the respondent.

Access Mode Alternatives and Covariates

Since it is one of the busiest airports in the United States, the number of ground transportation alternatives serving LAX exceeds those at other airports in the Southern California area. This demand analysis focuses on 10 major alternative ground passenger modes serving LAX: 1) drive and park at the airport, 2) drive and park at an offsite parking lot, 3) taxi, 4) car rental, 5) limousine, 6) private shuttle, 7) shared van/shuttle, 8) TNCs, 9) public transit, and 10) the Flyaway, a non-stop regional shuttle bus service to and from LAX. Additionally, some air travelers have the option to take a hotel courtesy shuttle or simply to be dropped off by others. Individuals staying at hotels with courtesy airport shuttles have a strong incentive to use them over other modes because they are essentially zero cost to the passenger and in many cases are door-to-door. Similarly, individuals who have the option to be dropped off by family members, friends, or relatives also have a strong incentive to choose this mode because they typically do not have to pay compensation. Thus, individuals who reported in the survey that their primary form of transportation to LAX was by hotel courtesy or dropped off were excluded.

The independent variables analyzed are travel time and cost. Travel time is computed from the driving option" of the Google API and is defined as total duration in the vehicle, whereas travel time by transit is defined as the sum of duration in the vehicle, walking to and from the stops, and waiting for transfers (if there are any transfers).

Not everyone has the same ground transportation choice set. But we did assume everyone has the option of taking a TNC, taxi, or limousine, while other modes are only available to some of the surveyed travel parties. As mentioned, depending on where they originated, some people

do not have the option of taking public transit. For the purpose of this study, whether or not public transit is available to an individual was determined through Google Maps. Although service by public and private shuttles is much more extensive by than public transit, they also have limited service areas.

The availability of public and private shuttles was determined through the major shuttle providers' websites (Primetime Shuttle, ShuttletoLAX, and SuperShuttle). For the regional "Flyaway" shuttle mode, we determined this was unavailable to individuals if the nearest Flyaway stop is located more than a 15-minute drive from their originating location. Lastly, we assumed that only Southern California residents have the options of driving and parking on- or off-site or using a rental car to go to the airport and return it there. The assumption that all residents can drive (their own vehicle or a rental) is plausible since most people in Southern California (especially those who can afford to fly) have access to a car[3]. The rental car option is unavailable to Southern California visitors because if they rented a vehicle for their trip, they must return it there (thus travelling to the airport by a rental car is the only choice for these individuals).

Description of the Alternative Modes

Passengers who reported that their primary form of transportation to LAX is private automobile either drove and parked on-site or drove and parked off-site. This is true even if the driver drops off passenger(s) at the terminal curb before parking. Parking at the airport is located in the Central Terminal Area. Currently, the daily parking rate at LAX is $30. Parking off-airport can be at any number of locations, but the most popular among them is at the Economy Parking

[3] The average vehicles per household in the city of Los Angeles is about 1.5 and this number increases with higher income (Governing the States and Localities (2015)).

Lot C, which is less than a mile from the airport. This lot also has a free shuttle that stops at each terminal. The daily parking rate there is $12.

Car rental companies are located in very close proximity to the airport, but none are on-site. Those taking a rental to go the airport must return the vehicle off-site and then board a free shuttle that stops at each terminal. The cost of a car rental is estimated here to be about $76.00 per day (assuming it was picked up somewhere not at the airport and then returned at the airport).[4]

Public transit in Los Angeles does not directly drop off passengers at airport terminals, so transit users must also board shuttles to transfer from an off-site location to the airport. Public transit in Los Angeles consists of MTA (Metro) buses and light rail lines, Santa Monica/Big Blue Bus, Culver City Bus, and Torrance Transit. Those who take Metro rail and bus lines can take a free shuttle at the Metro Green Line Aviation Station, and those who take other public buses can take a shuttle from the Metro Bus Center. These shuttles stop at every terminal, which means that passengers have longer travel times than if being dropped off directly.

Unlike driving and parking off-site, rentals, or public transit, the Flyaway and the shared van/ shuttle options take passengers directly to the airport terminals, but they stop at each terminal at LAX because they are shared modes and thus have multiple drop-offs. As mentioned, the Flyaway is a direct shuttle bus service to and from LAX. Its 2015 stations were located in Van Nuys, L.A. Union Station, Westwood, Hollywood, and Santa Monica. Applicable one-way fare is $8 per person for all of the Flyaways, except the Westwood Flyaway, which costs $10.

[4] The cost of the rental is higher than if the vehicle was returned at the same location where it was picked up. The estimate is based on rates by enterprise.

Shared vans/shuttles, operated by Super Shuttle or Primetime Shuttle, are shared door-to-door services. For passengers who travel from any part of a large service area in Southern California where these shuttles operate and they reserve the shuttle 24 hours in advance, the fare is a fixed $21 for the first person and $14 for each additional rider, independent of distance (ShuttletoLAX).

Reservations made less than 24 hours before the pickup, or for rides outside of the service area, have different pricing schemes that depend on distance, location, and party size (ShuttletoLAX, SuperShuttle, and Primetime Shuttle).

Other alternatives, such as private shuttles, limousines, taxis and TNCs do not stop at every terminal and directly take passengers to their boarding terminal.[5] Because they are private, these modes pick up and drop off only one party (or typically two at the most) and thus often have much shorter travel times than shared vans/shuttles. Private shuttles are similar to shared vans/shuttles, except they are nonstop services and direct to destination as they do not pick up or drop off other parties. In fact, Primetime Shuttle runs a variety of private shuttle services in addition to their shared vans/shuttles. Their standard van service, private or shared, seats a maximum of seven people.

Other than its standard vans, Primetime Shuttle offers other private shuttle services, including the Execucar Sedan service, the Execucar SUV service, and the Business Express SVC by Express Shuttle, all of which include a driver. These services usually have a maximum of three, four, and five passengers, respectively. Based on the pickup locations, some nonstandard shuttle services may vary or be unavailable (Super Shuttle, and Primetime Shuttle).

[5] TNC services like Uber Pool or Lyft lines may have more than one party, but the maximum number of separate travel parties and stops is two.

Another direct access mode is a limousine. Although a stretched limousine can be very luxurious and provide seats for many passengers, these vehicles often do not have adequate trunk space for luggage. Therefore, the maximum number of seats in a limousine available for passengers traveling to LAX is actually lower than if they were not going to the airport (LAX Limousine Service).

Taxi and TNCs are the final set of direct airport access modes. Taxi companies operating in the Los Angeles have a minimum fare of $2.85 and, after the first 1/9 of a mile, the fare is $2.70 per mile (Taxicabsla (2015)). TNC fares were estimated based on the costs of Uber. At the time, services in Los Angeles had a booking fee of $1.65, a per-mile cost of about $0.90, and a minimum fare of $4.65 (Uber). The actual per-mile charge may vary depending on traffic, discounts or promotions, or surge (i.e., peak load) pricing.

We use the various descriptions above to help estimate the travel time and trip cost by each mode for travelers to LAX relative to their own pickup location. The travel costs were further adjusted[6] by travel duration (number of days) and party size.

Model Specification

In our model development, the utility of each decision maker, n, for each alternative, a, is assumed to be a linear function of travel cost, travel time, and an alternative-specific constant (ASC). Under the multinomial logit model specification, error terms are assumed to be drawn from independent and identically distributed extreme value distribution. The 10 alternatives chosen for the analysis cannot share common unobservable characteristics or their error terms will not be independent. Further, travel time and cost coefficients are general and do not vary

[6] Each observation in the passenger survey had different travel durations (number of days) and party size. Our adjustments for total travel time and costs were done in a standard way; for example, we multiplied the number of passengers in the travel party by the cost of individual bus fares to get the total bus fares.

over alternatives. Moreover, we assume the TNC modal alternative is fixed, making it the baseline for our alternative-specific constants.

(1) $$U_{na} = ASC_a + \beta_{cost} \cdot Cost_{na} + \beta_{time} \cdot Time_{na} + \varepsilon_{na} = V_{na} + \varepsilon_{na}$$

(2) $$P_{na} = \frac{e^{V_{na}}}{\sum_{a \epsilon A} e^{V_{na}}}$$

Following the utility specification shown in equation 1, equation 2 lists the associated multinomial logit probability of making a choice (Ben-Akiva and Lerman (1987)).

We noted that modes such as limousine, drive and park on-site, and drive and park off-site are private, while public transit and shared van/shuttle are shared with multiple and different parties. Any of the private modes might be correlated with each other because they share many characteristics. Specifically, they do not put strangers in the same vehicle and they do not have multiple drop-offs and pickups. For the same reasons, shared modes might be correlated because they do put strangers in the same vehicle and they have multiple drop-offs and pickups. And since there are similarities besides travel time and costs between the alternatives, their error terms may not be independent.

This issue is not a problem for our analysis since we developed nested logit models to mitigate this concern. Formally, within a nest d, alternatives are correlated through the same error, while across the specified nests, the errors are assumed to be i.i.d. More generally, the nested logit marginal and conditional probabilities (Ben-Akiva and Lerman 1987) are given by:

(3) $$P_{na|d} = \frac{e^{V_{na|d}}}{\sum_{a \epsilon A(d)} e^{V_{na|d}}}$$

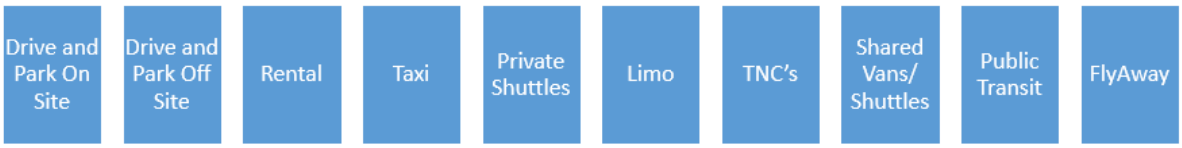
(4) $$P_{nd} = \frac{e^{(\alpha_{nd} + \alpha_x \cdot X_{nd} + \tilde{V}_{nd})}}{\sum_{d \epsilon D} e^{\alpha_{nd} + \alpha_x \cdot X_{nd} + \tilde{V}_{nd}}}$$

In general, X_d are variables that vary within the nest (for example, in the transit nest, it may be a factor such as headway), but we did not have access to such variables in our study. In addition, the inclusive value $\tilde{V}_{nd} = \frac{1}{\mu_d} \ln[\sum_{a \epsilon A(d)} 1^{e^{(V_{na|d})\mu_d}}]$, and $0 < \frac{1}{\mu_d} < 1$ or $\mu_d > 1$ (Ben-Akiva and Lerman 1987). The various nesting structures are shown in Figure 5.1 (below)

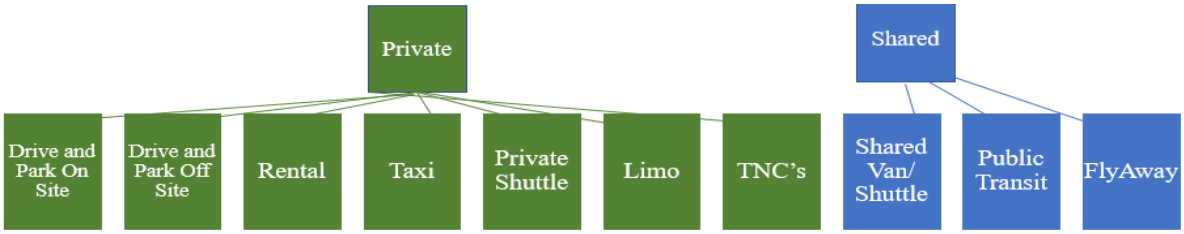
In addition to the multinomial logit specification (Fig. 5.1.1), we test a nested logit model, consisting of two nests that separate shared and private modes (Fig. 5.1.2). Each of our chosen nests has two levels. To list alternatives, these are: drive and park at the airport, drive and park at an offsite parking lot, rentals, taxi, TNC, limousine, and private shuttle fall into the first category, while shared van/shuttle, Flyaway, and public transit fall under the second category. A limited number of TNC services can be shared with up to two different parties, but they are considered private in this study since we believe that this alternative is predominantly the standard UberX and Lyft services.

We also tested other nesting and hierarchical structures. In Fig. 5.1.3, the nested logit model has a nest grouping all modes that require driving (drive and park on site, drive and park off site, and car rental), and a second nest encompassing all ride services (taxi, TNC, shared vans/ shuttles, private shuttles, and limousines), with a final nest containing all transit and non-door-to-door modes (public transit and the Flyaway). Under that specification, each nest contains two levels, while in Fig. 5.1.4, only some nests contain two levels. In Fig. 5.1.4, modes that are ride services are no longer grouped under one category, while modes that require driving and modes that are transit and non-door-to-door are grouped in their corresponding nests. In this specification, taxi, private shuttles, limousines, TNCs, shared vans/ shuttles (all modes that require driving) and all modes that are transit and non-door-to-door are assumed to be distinct from each other, meaning that they do not share common unobservables.

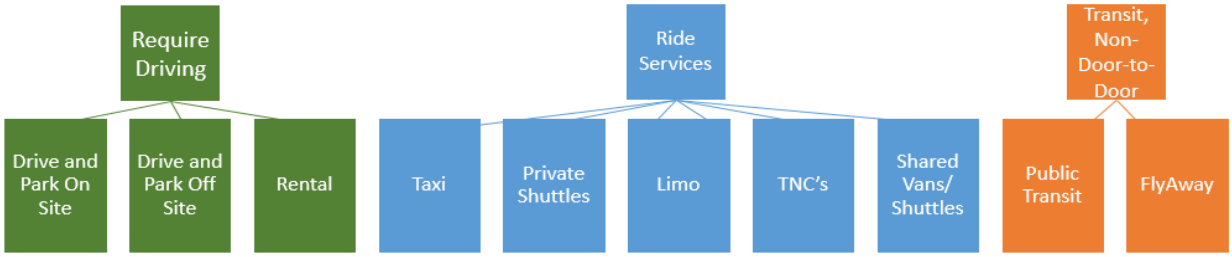
5.1.1. Multinomial Logit Model



5.1.2. Nested Logit Model with Two Nests - Private and Shared



5.1.3. Nested Logit Model with Three Nests - Require Driving, Ride Services, and Transit, Non-Door-to-Door



5.1.4. Nested Logit Model with Seven Nests - Require Driving, Transit, Non-Door-to-Door, Taxi, Private Shuttles, Limousines, TNCs, and Shared Vans/ Shuttles

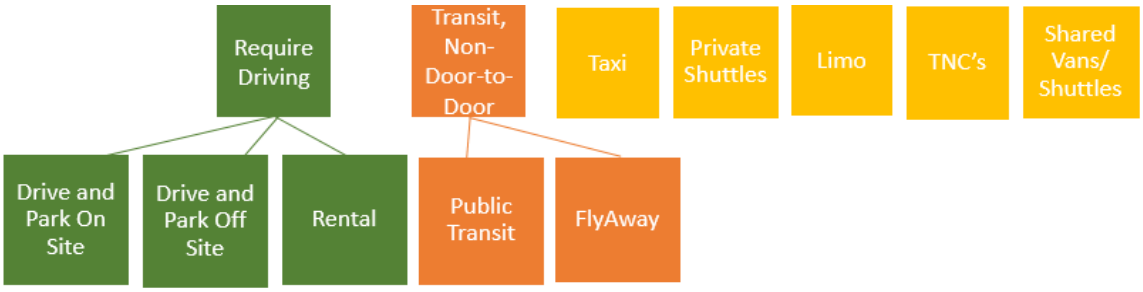


Figure 5.1. Nesting Structures

Finally, we suspect that there might be additional disparities in airport access decisions between business and leisure passengers. Those who fly for business are typically reimbursed for their travel and thus tend to be somewhat less sensitive to travel cost. And if an individual is

traveling for business, they are probably less flexible to longer travel time duration as compared to people traveling for leisure. Given this, the coefficients of the travel cost and travel time variables (as well as other characteristics beside travel cost and travel time) may not be the same for passengers traveling for different purposes. Thus, we also test for market segmentations under different travel purposes, here represented by mainly business vs. leisure passengers. All econometric specifications presented in this research were estimated with the public domain BIOGEME software.[7]

5.3 Ground Transportation Alternatives (Travel Time and Cost Comparisons)

Descriptive Statistics

On a broader level, how do travel times and costs of TNCs compare to those of other ground transportation modes? Table 5.1 shows average travel times and costs by each mode from downtown LA, for zip code 90012. We chose this area as a reference example because it is located in the downtown area, 20 miles from LAX and also contains important sites like Union Station. The average travel cost estimates are calculated for one-way trips to the airport and based on a travel party size of one person, while parking cost is based on a trip length of about three days. Travel time estimates are calculated for one-way trips as well.

From the start, a significant tradeoff between travel time and cost among the modes is apparent. Public transit, the Flyaway, and shared vans/shuttles cost about $5, $8, and $21 respectively, while the other modes (not including TNCs) start at about $40. The former travel times are at least 80 minutes duration in our sample. This is much longer than the more expensive modes, which generate an average travel time of about 45 minutes. And as mentioned,

[7] Biogeme, developed by Michel Bierlaire at the Ecole Polytechnique Fédérale de Lausanne, Switzerland, is an open source freeware designed for the maximum likelihood estimation of parametric models in general, with a special emphasis on discrete choice models.

TNCs are of special interest in this market because they have both low prices and low travel times.

Table 5.1. Cost and Travel Time Example from Downtown LA (zip code 90012) By Mode

Mode	Avg. Cost* ($)	Avg. Travel Time (Min.)
Drive and Park Off Site	55.19†	74.8
Drive and Park On Site	121.94†	45.3
Rental	87.14	60.0
Flyaway	8.00	91.0
Limo	177.00	30.3
Private Shuttle	40.00	30.3
Shared Van/Shuttle	21	89.8
Public Transit	4.61	82.2
TNCs	28.65	30.3
Taxi	51.88	30.3

*Travel party size=1, †About 3 days of parking

Among the private modes, we find that a TNC is usually the most competitively-priced option. Fares charged by a TNC in general (from downtown or elsewhere) amount to only about 55% of equivalent taxi costs. From downtown, the average cost of a TNC ride at $28.65 is much lower than the average cost of taxis at $51.88, car rental at $87.14, drive and park at the airport at $122, or limousine at $177. It is also slightly less than private airport shuttles at $40, or the drive and park off-site at $55. Note that those who drive and park offsite, where parking is least expensive, still incur a higher average travel cost than someone using TNCs. However, compared to shared modes at LAX, TNCs are costlier. Public transit has the lowest average cost of all modes, at $4.61, followed by the Flyaway at $8.00. Shared vans/shuttles on the other hand cost an average of $21, not much different than the cost of TNCs.

In addition to providing one of the more affordable services, we see that TNCs also have comparatively low travel times. Based on our estimates originating from downtown LA, a TNC can get passengers to the airport in about one third of the time as compared to those modes with the greatest travel times. For the downtown origin, shared vans/shuttles and public transit have

average travel times of 89.8 minutes and 82.2 minutes respectively, while TNCs generate an average travel time of only about 30.3 minutes. We also find that taxis, private shuttle, and limousines have approximately the same average travel time as TNCs. These latter modes, including TNCs, have low travel times to LAX for good reason - passengers do not have to transfer, park, or take an off-site shuttle. Additionally, they also have fewer pickups and drop-offs since they are private by definition. All told, since TNCs are among the least expensive ground transportation options and also generate one of the lowest travel times, their services seem to provide a very competitive alternative for travelers heading to LAX.

Table 5.2 shows the availability and share of each ground transportation mode. Some modes are very limited in access and available to only about half of our sample. For example, recall that because the modes “Drive and Park Off-Site”, “Drive and Park On-Site”, and “rentals” are assumed to be available only to Southern California residents, only about 48% of the sample have access to these transportation options. The Flyaway service is available to about 41% of our sample since there are only five Flyaway stations. Many more individuals have the option of private shuttles, shared vans/shuttles, and public transit because these alternatives are available to both local residents as well as visitors, and they have greater coverage areas. These latter options are available to 97%, 89%, and 91% of the sample, respectively.

Our final sample contains 3,096 unique travel parties consisting of airline travelers originating their travel (but not connecting) at LAX. As mentioned, we dropped observations where the respondents chose an unavailable alternative. Of the 3,096 travel parties, 550 (17.8%) used Uber or Lyft. Even though TNCs were significantly less costly than taxis, a higher percentage of people (about 18.4%) took a taxi to the airport, and in fact taxis were the most frequently used alternative mode. Other modes comparable in use to TNCs were the private and

shared shuttles, which had shares of 17.3% and 12.2% respectively. Alternatively, some of the least frequently used modes were public transit at 1.5%, car rentals at 2.9%, Flyaway at 4.6 % and limousines at 6.4%.

Table 5.2. Percent Mode Available and Mode Share

Mode	If Limited Availability, % Available	Mode Share (N) Total 3096	Mode Share (%)
Drive and Park Off Site	48	315	10.2
Drive and Park On Site	48	269	8.7
Rentals	48	90	2.9
Flyaway	41	141	4.6
Limo	-	199	6.4
Private Shuttle	97	537	17.3
Shared Van/Shuttle	89	378	12.2
Public Transit	91	46	1.5
TNCs	-	550	17.8
Taxi	-	571	18.4

5.4 Model of Ground Transportation Mode Choices

We conduct a series of likelihood ratio tests and list them in Table 5.3 below. The first three are to formally compare choice specifications and to determine potential need for generalized extreme value models (nested logit), rather than simple multinomial logit (Ben-Akiva and Lerman 1987).

First, we tested multinomial logit vs. two nest nested logit. Under the null hypothesis, both the log sum term (inclusive value) coefficients for the private and shared nests equal to unity (multinomial logit), whereas the alternative was that at least one of the log sum term coefficients was not equal to unity (nested logit). As shown in the table, the null (the simple logit model) was rejected, while the two nests nested logit model cannot be rejected. Subsequently, we tested the multinomial logit model against nested logit specifications with three nests, and a

multinomial logit model against a nested logit model with seven nests. Similarly, we rejected the multinomial logit specification in the latter tests.

Table 5.3. Specification Testing (Using Likelihood Ratio (LR) Test)

Multinomial Logit vs. 2 Nests NL H_0: $\mu_{\text{private}} = \mu_{\text{shared}} = 1$ H_A: at least one μ_{private} or $\mu_{\text{shared}} \neq 1$ LR: -2 × (L_R- L_U)= $-2 \times (-5602.757 + 5599.911) = 5.692$ 5.692 > 4.61 (the critical value of the chi-square distribution with 2 degrees of freedom at a 90% level of confidence) ∴ Reject the Null, or there is evidence of correlation between the alternatives in the multinomial logit model
Multinomial Logit vs. 3 Nests NL H_0: $\mu_{\text{requires driving}} = \mu_{\text{ride services}} = \mu_{\text{transit,non-door-to-door}} = 1$ H_A: at least one $\mu_{\text{requires driving}}$, $\mu_{\text{ride services}}$, or $\mu_{\text{transit,non-door-to-door}} \neq 1$ LR: -2 × (L_R- L_U)= $-2 \times (-5602.76 + 5593.755) = 18.004$ 18.004 > 6.25 (the critical value of the chi-square distribution with 3 degrees of freedom at a 90% level of confidence) ∴ Reject the Null, or there is evidence of correlation between the alternatives in the multinomial logit model
Multinomial Logit vs. 7 Nests NL H_0: $\mu_{\text{requires driving}} = \mu_{\text{Taxi}} = \mu_{\text{Limousine}} = \mu_{\text{Private Shuttle}} = \mu_{\text{Shared Vans/Shuttles}} = \mu_{\text{TNC's}} = \mu_{\text{transit,non-door-to-door}} = 1$ H_A: at least one $\mu_{\text{requires driving}}$, μ_{Taxi}, $\mu_{\text{Limousine}}$, $\mu_{\text{Private Shuttle}}$, $\mu_{\text{Shared Vans/Shuttles}}$, $\mu_{\text{TNC's}}$ or $\mu_{\text{transit,non-door-to-door}} \neq 1$ LR: -2 × (L_R- L_U)= $-2 \times (-5602.76 + 5593.755) = 18.004$ 18.004 > 12.00 (the critical value of the chi-square distribution with 7 degrees of freedom at a 90% level of confidence) ∴ Reject the Null, or there is evidence of correlation between the alternatives in the multinomial logit model
7 Nests NL vs. 3 Nests NL H_0: $\mu_{\text{Taxi}} = \mu_{\text{Limousine}} = \mu_{\text{Private Shuttle}} = \mu_{\text{Shared Vans/Shuttles}} = \mu_{\text{TNC's}} = 1$ H_A: at least one μ_{Taxi}, $\mu_{\text{Limousine}}$, $\mu_{\text{Private Shuttle}}$, $\mu_{\text{Shared Vans/Shuttles}}$, or $\mu_{\text{TNC's}} \neq 1$ LR: -2 × (L_R- L_U)= $-2 \times (-5593.755 + 5593.755) = 0$ 0 < 9.24 (the critical value of the chi-square distribution with 5 degrees of freedom at a 90% level of confidence) ∴ Fail to reject the Null, or there is not enough evidence to rule out model with no error correlation between the alternatives: taxi, limousine, private shuttle, shared vans/shuttles, and TNCs
No Market Segmentation vs. Market Segmentation between Business and Leisure Passengers $\mathbf{H_0}$: $\boldsymbol{\beta}_{\textbf{just business passengers}} = \boldsymbol{\beta}_{\textbf{just leisure passengers}}$ $\mathbf{H_A}$: $\boldsymbol{\beta}_{\textbf{just business passengers}} \neq \boldsymbol{\beta}_{\textbf{just leisure passengers}}$ ** **where β are the estimated coefficients in (1)** LR: -2 × (L_R- L_U)= $-2 \times \left(-5146.913 - (-3456.592 - 1647.356)\right) = 85.93$ 85.93 > 19.80 (the critical value of the chi-square distribution with 13 degrees of freedom at a 90% level of confidence) ∴ Reject the Null, there is evidence of market segmentation (taste variations) between business and leisure passengers.

In the fourth test conducted in Table 5.3, we compared a nested logit model with seven nests against one with only three nests, also using a likelihood ratio test[8] (Ben-Akiva and Lerman 1987). We failed to reject the model with seven nests, which also suggests that there is no error correlation between the following alternatives - taxi, limousine, private shuttle, shared vans/shuttles, and TNCs. Thus, our findings indicate that perhaps these modes should not be grouped together.

Our final specification test is more policy oriented. It explores the possible taste variations between business and leisure passengers. We re-estimated a nested logit model with seven nests for both business and leisure passengers, then just with business passengers, and then just with leisure passengers. From the first estimate, we attain a restricted log likelihood, while the remaining two (summed) give us the unrestricted log likelihood. In sum, we reject the null hypothesis that there was no market segmentation between business and leisure passengers, suggesting a future need to separate model specifications for business and leisure passengers.

In summary, based on a series of likelihood ratio specification tests, we conclude that the multinomial logit specification is inadequate, as some alternatives seem to share common unobservables. Additionally, we find that alternatives that seem to possess error correlation are modes that require driving and modes that are transit related and non-door-to-door, whereas the remaining modes do not seem to possess notable error correlations. Lastly, the specification tests also suggest a need to estimate choice models for airport transportation separately for business and leisure passengers because the two types of passengers clearly have different tastes.

[8] The two models are nested in a sense that all terms of a smaller model (nested logit with seven nests) occur in a larger model (nested logit with three nests). This is a necessary condition for using most model comparison tests like likelihood ratio tests.

Table 5.4 highlights the output from the chosen model, a nested logit model with seven nests for both leisure and business passengers. For both models of leisure and business passengers, estimates of the covariates have expected signs. Since travel time and travel cost coefficients are significant and negative, this demonstrates that they have a significant impact on modal choice in that higher travel time or travel cost leads to a lower probability of that mode being chosen. Next, the implied value of travel time savings per hour from the estimates are calculated as follows: $\frac{\beta_{time}(\$)}{\beta_{cost}(\text{min})} \times \frac{60\ \text{min}}{\text{hour}}$ (Ben-Akiva and Lerman 1987). For business passengers in the sample, we find that their value of time is approximately $157/hr, while for leisure passengers in the sample it is about $103/hr. Of course, this computed value of time is specific to only to travel and from LAX – and is interesting because both are greater than an expected value of time for either group as proxied by the wage rate in the region. However, we note that this computed value falls within the range found in previous airport access mode studies, including Landau et al. (2015).

Table 5.4. Nested Logit with Seven Nests, Leisure versus Business Passengers

	Leisure				Business			
Description	**Estimated Coefficient**	**Standard Error**	**t-stat (0)**	**p-val (0)**	**Estimated Coefficient**	**Standard Error**	**t-stat (0)**	**p-val (0)**
Alternative Specific Constants:								
Drive and Park Off Site	1.84	0.162	11.36	0	1.61	0.278	5.78	0
Drive and Park On Site	1.74	0.148	11.73	0	1.85	0.209	8.86	0
Flyaway	0.65	0.201	3.25	0	-0.47	0.340	-1.38	0.17*
Limousine	-0.29	0.143	-2.00	0.05	0.48	0.216	2.21	0.03
Private Shuttle	0.34	0.078	4.38	0	-0.23	0.121	-1.93	0.05
Shared Vans/ Shuttle	1.00	0.186	5.37	0	0.40	0.323	1.24	0.21*
Public Transit	-0.89	0.291	-3.05	0	-2.16	1.800×10^{308}	0.00	1.00*
Rental	0.44	0.192	2.29	0.02	-0.67	0.408	-1.64	0.10
TNCs	0.00	--fixed--			0.00	--fixed--		
Taxi	0.22	0.083	2.61	0.01	0.39	0.106	3.69	0
Covariates:								
Travel Cost ($)	-0.00605	0.000705	-8.58	0	-0.00952	0.00125	-7.6	0
Travel Time (Minutes)	-0.0158	0.00259	-6.09	0	-0.0164	0.00487	-3.36	0
Inclusive Value Coefficients ($1/\mu$):			**t-stat (1)**	**p-val (1)**			**t-stat (1)**	**p-val (1)**
Requires Driving Nest	0.72	0.175	2.24	0.02	1.00	0.126	0.01	0.99*
Ride Services Nest	1.00	--fixed--			1.00	--fixed--		
Transit, Door-to-Door Nest	0.77	0.265	1.15	0.25*	0.52	1.800×10^{308}	0.00	1.00*
Additional Information:								
Number of Estimated Parameters		13				13		
Number of Obs.		1884				925		
Final Log Likelihood		-3456.592				-1647.356		

In the model exclusive to leisure passengers, the alternative specific constants (ASC) for all of the modes are significant. Again, we used TNC as the baseline for the ASC's. Because the ASC for taxis is significant and positive this suggests that, ceteris paribus, taxis are preferred over TNCs. In fact, in this sample, most of the other modes, holding everything else constant, are preferred to TNCs as well, including alternatives such as drive and park on-site, drive and park off-site, Flyaway, car rentals, and private and shared shuttles. The only alternatives that were found to be less preferred to TNCs (all else equal) were limousines and public transit.

The last three estimates to examine for this specification are the inclusive value coefficients of the chosen nests. In this likelihood ratio test, we examined whether: $\mu_{\text{requires driving}} \neq 1, \mu_{\text{ride services}}$ and $\mu_{\text{transit,non-door-to-door}} \neq 1$ was valid. But we can also examine whether just one or some of the inequalities are true ($\mu_{\text{requires driving}} \neq 1$, or just $\mu_{\text{transit,non-door-to-door}} \neq 1$), using a t-test (Ben-Akiva and Lerman 1987). The p-value with respect to $\mu_{\text{requires driving}} = 1$ is 0.02. Since the p-value is less than 5%, this indicates that the coefficient for $\mu_{\text{requires driving}}$ is significantly different from 1, meaning we can conclude there is significant correlation between the alternatives in the "requires driving" nest and that the alternatives in that nest should be grouped together. In contrast, the alternatives in the "transit, non-door-to-door" nest are not significantly different from 1, with a p-value with respect to $\mu_{\text{transit,non-door-to-door}} = 1$ of 25%, meaning there is not enough evidence to show that the modes in that nest should be grouped together.

In the specification exclusive to business passengers, we found that many of the ASCs are significant, except those for public transit, shared vans/shuttles, and FlyAway. Note that not only is the ASC of public transit insignificant, but its standard error is very large. We believe this may be due to the fact that very few business passengers took public transit to go to LAX (only

about six people in the sample), making the sample size applicable to this mode choice extremely limited. Additionally, the estimates suggest driving and parking on or off site, limousines, shared vans/shuttles, and taxis are all preferred over TNCs, all other things being equal, while Flyaway, private shuttles, public transit, and rentals are less preferred to TNCs.

Again, the last three estimates in the model are the inclusive value coefficients of our chosen nests. In this case, the coefficients are not significantly different from unity for the "requires driving" and "transit, non-door-to-door" nests. In fact, the inclusive value coefficient of the first nest is estimated to be equal to unity. Perhaps to business passengers, driving and parking on site, driving and parking off site, and rentals do not share some common unobservables or belong in a group. Meanwhile, the inclusive value coefficient of the third nest is estimated to be about 0.52.[9]

5.5 Scenario Analysis: Passenger Sensitivities to Changes in TNC Travel Time and Cost

The probabilities of choosing a TNC for each decision maker were calculated using the estimated coefficients of the linear utility functions. The average of these probabilities is the projected demand for TNCs (Table 5.5). Currently, TNCs account for 17.8% of the market among the alternatives we considered. If the TNC demands for passengers traveling on business and leisure are evaluated separately, they are estimated to be about 16.8% and 19.8%, respectively.

Possible changes to modal charges or costs, such as a 10% increase in TNC fares, an increase in TNC fares to match taxi fares, or a 50% fare cut plus 10-minute travel time increase,

[9] The closer this value is to 0 means that alternatives in the nest are very similar and probably belong in a group; however, it is not significant.

are considered. These scenarios are simulated by calculating the equivalent probabilities using the estimated coefficients, but changing the prices and or travel times of TNCs.

The first scenario (10% increase in TNC fares) can be expected to lower the demand for TNCs to about 16.4% for business passengers and 19.2% for leisure passengers, or respectively, 2.5% and 2.7 % decreases relative to the initial TNC shares. It seems that increasing TNC's cost by 10% does not affect demand very much.

The second event (increase in TNC fares to match taxi fares) is also expected to lower the demand for TNCs but by a much greater degree. In this scenario, prices had to be almost doubled (about 80% increase). The projected demands for TNC services of business and leisure passengers respectively were 13.9% and 16.0%. These represent a 20.9% drop with respect to the initial TNC share for business passengers and a 23.3% drop with respect to the initial TNC shares for leisure passengers.

Table 5.5. Projected Demand for TNCs Under Various Price & Travel Time Changes

	Business	Leisure
Initial Share Using TNC (%)	16.83	19.76
With 10% TNC Price Increase	Business	Leisure
Share Using TNC With Price Increase (%)	16.42	19.24
Change Relative to Initial TNC Share (%)	-2.5	-2.7
With TNC Price Increase to Match Taxi Fares	Business	Leisure
Share Using TNC with (≈ 80%) Price Increase (%)	13.92	16.03
Change Relative to Initial TNC Share (%)	-20.9	-23.3
With 50% TNC Price-Cut & 10 min. Travel Time Increase	Business	Leisure
Share Using TNC With Carpooling Changes (%)	16.80	19.99
Change Relative to Initial TNC Share (%)	-0.2	1.2

Since the drop in demand is smaller for business passengers in the first two cases, it seems that business passengers are less responsive to modal price hikes. As found in other studies of business travel, people traveling on business are far less sensitive to price changes than

those traveling for pleasure or personal reasons, most likely because their time is considered to be more valuable, and also that they might not be personally liable for the cost of their travel.

Finally, the third simulated change (50% fare cut plus 10-minute travel time increase, which represents the difference that would be imposed by pooled TNC services) is projected to decrease the demand for TNCs by business passengers by about 0.2% (relative to initial share), while increasing the demand for TNCs by leisure passengers by about 1.2% (relative to initial share). Essentially, we consider these values insignificant.

5.6 Conclusion

Using Google Maps and various other data sources, we estimated travel time and trip cost by each mode for ground travelers to LAX relative to his or her pickup location. Our estimated travel costs reflect each travel party's travel duration (number of days) as well as party size.

We found that in the absence of TNC services as a modal alternative, many air travel passengers heading to LAX would face stark tradeoffs between long travel times and high travel costs. They could choose a mode like shared vans/shuttles that do not cost a lot but are characterized by multiple pickups and drop-offs generating long travel times. Alternatively, they can choose a mode like taxi which costs considerably more but is private and direct. Meanwhile, few passengers to LAX take public transit because those modes have even longer travel times than shared vans/shuttles and unlike many major US cities, there is no direct rail service to LAX.

Multinomial logit and nested logit models of airport ground transportation decisions were estimated to help understand the drivers of current market shares of TNCs in this large market. Our measured travel time and trip cost by each mode were used as inputs. We also used our specifications to simulate demand for TNCs under policy events like regulated fare increases or decreases combined with a small modal travel time increase.

Likelihood ratio tests rejected the simple multinomial logit structure of demand estimation in this ground transportation market. Our preferred specification is nested logit. Statistical tests also provide some insights on how the alternatives should be grouped for this market, i.e. grouping all modes that require driving, grouping all modes that are transit and non-door-to-door, while we find that remaining modes seem to be dissimilar to each other. Finally, testing suggested a need to estimate separate models for airport destined passengers traveling with different purposes (business and leisure). After considering the simulation scenarios (increasing the cost of TNC rides by 10%, increasing the cost of TNC rides to match the cost of taxis, or cutting TNC fares for a 10-minute travel time increase), we find that these policy shocks would have differential effects on passengers traveling for business or for leisure. By way of example, in our second simulated scenario (a TNC fare increase to match the cost of taxis), the expected drop in demand for TNC (relative to the initial demand for TNC services) was estimated to be about 21% for business passengers and about 23% for leisure passengers. With respect to ground transportation at LAX, business passengers appear to be slightly more sensitive to travel time while leisure passengers are more sensitive to travel costs.

Future research will focus on improving airport ground access mode choice models by making them more robust. In addition, we plan to apply the methodology to explore the impacts of other relevant scenarios, such as an increase in the cost of airport parking.

Chapter 6

Optimized TNC Ride Service to the Airport

6.1 Introduction

Several factors cause airport curbside congestion--increasing volumes of air passengers, peak departure and arrival times, terminal and curbside design (Madle et al. (1982)). Mode choice and high use of private modes also impact curbside congestion. With the advent of Transportation Network Company (TNC) service at the airport, many air passengers are replacing shared modes (modes that typically have higher vehicle occupancy such as light rail, bus, or airport shuttles that can seat up to eight passengers) with private TNCs (Hermawan and Regan (2018)). In 2015, TNCs caused 215,000 and 25,000 passengers to switch from shared to private modes at San Francisco International Airport (SFO) and Oakland International Airport (OAK), respectively. By 2020, they expect the shifts to be about 840,000 and 107,000 passengers per year, at the respective airports. These substitutions in shared modes have implications on curbside congestion. To mitigate such impacts, this study proposes applying the pickup and delivery problem to better match passengers going to the airport by shared (pooled or multi-passenger) TNC service. Pooled passengers will have minimal detours, and in some airports like LAX where the ground transportation modes are either very expensive and fast or inexpensive but extremely slow (Hermawan and Regan (2017)), this service would provide a more moderate alternative (in price and travel time) for air passengers going to the airport.

6.2 Data and Methodology

Requests are formed based on actual air passenger data from the 2015 Los Angeles International Airport (LAX) Passenger Survey. This extensive survey interviewed over 13,000

departing passengers at LAX boarding gates, over the course of two, non-consecutive weeks in 2015 (April 13th-19th and July 13th-19th). Respondents either started their trip at LAX or they were connecting at LAX. Participants were asked over 100 questions about their trip, ride to the airport, and demographics. Such questions include: whether they are traveling internationally or domestically and for business or leisure, what is their travel party size, and how many days they will be away or how many days they stayed in Southern California. They also asked what mode was used to go to the airport, and the location prior to accessing the airport. They did not collect information on duration or cost of the ride to the airport. Demographic questions include whether they are U.S. residents, whether they are Southern California residents, and what is their income, gender, and age.

From the survey data, only trips that started at LAX, of passengers flying alone, and on one of the days (July 18th, 2015) were considered. This includes a sample of 334 passengers or travel parties of size one. The study focuses on solo flyers who start their trip at LAX because they are the easiest to pool in the initial analysis. Large parties would presumably travel to the airport together and thus not use a pooled TNC. Moreover, a majority of passengers departing out of LAX, fly alone. In the passenger survey, 50% of the respondents claimed to have a travel party size of one. The service also has a limit on the coverage areas. For example, it would not serve a request from San Francisco (385 miles away from LAX). In the survey, the indicated locations before heading to the airport are all over Southern California, while a few are not. Figure 6.1 shows some of these locations (in yellow) and the location of the airport. Those who indicated that their location before heading to the airport is very far away (having a travel time of over an hour and 40 minutes), were also excluded. The final sample size is 318 passengers or requests.

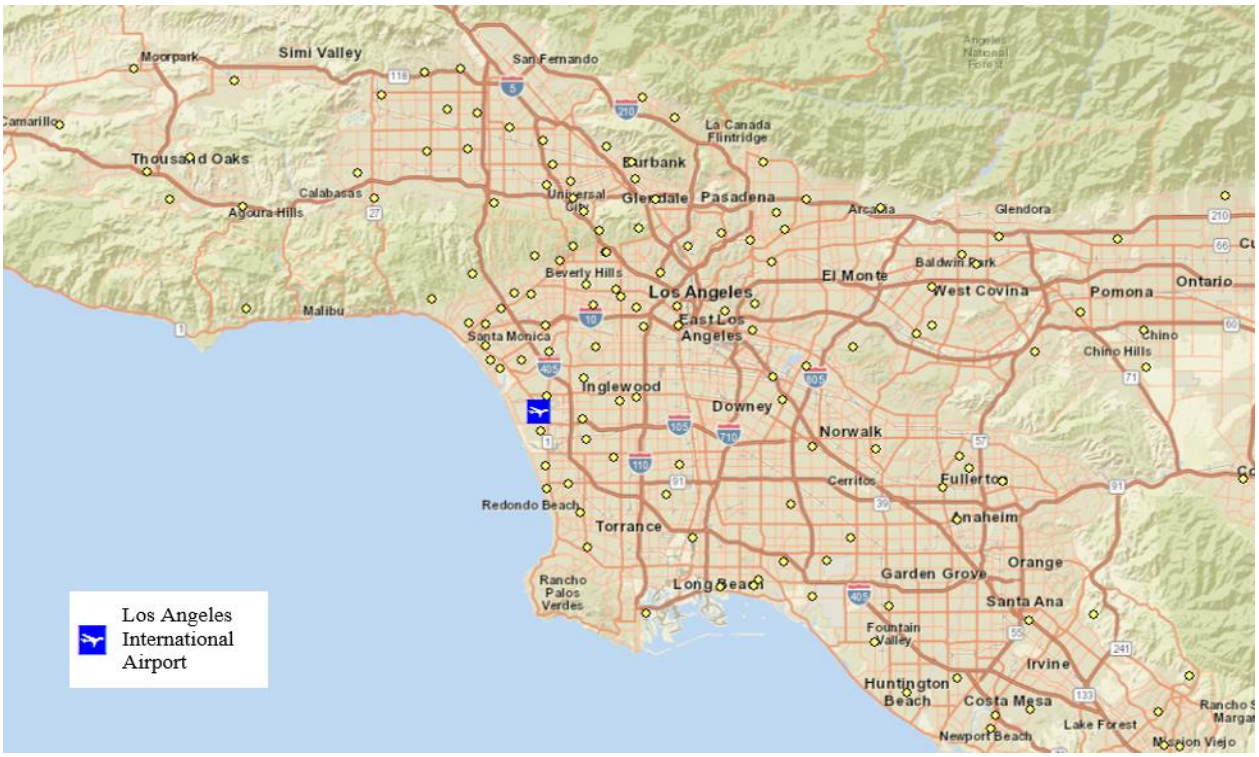


Figure 6.1. Pick-Up Locations

The Pick-Up and Delivery Problem with Time Windows and Capacity Constraints (PDPTWCC)

The PDPTWCC formulation used here is based on Dumas et al. (1991). We implemented the optimization solver using the Gurobi Optimizer[10]. Because the PDPTWCC increases in complexity rapidly with additional number of requests, we solve multiple PDPTWCC, each with a small number of requests. For each group, the requests are clustered by similar arrival times.

Notation

There are n customers (or n requests), indexed by i. The pick-up location of customer i is i, while his or her drop-off location is $(n+i)$. The set of all pick-up locations is denoted as P^+ and the set of all the drop-off locations is P^-. The set of all pick-up and drop-off locations or the union of the two is P. Originating depot is denoted as 0 and last depot is denoted as $(2n+1)$. The

[10] The Gurobi Optimizer is a commercial optimization solver for linear programming (LP), quadratic programming (QP), quadratically constrained programming (QCP), mixed integer linear programming (MILP), mixed-integer quadratic programming (MIQP), and mixed-integer quadratically constrained programming (MIQCP).

set of all nodes (which includes the pick-up and drop-locations and originating and last depots) is denoted as *N*. Nodes may correspond to the same physical locations. In this study of trips to the airport, all of the requests' delivery nodes share the same physical location, namely the airport.

In request *i*, d_i is the number of passengers that must picked-up at location *i* and dropped-off at location (*n*+*i*). $[a_i, b_i]$ and $[a_{n+i}, b_{n+i}]$ are the time windows for customer *i*'s pick-up and drop-off respectively. $[a_0, b_0]$ and $[a_{2n+1}, b_{2n+1}]$ are the time windows for respectively, the departure from the originating depot and the arrival back to the last depot.

The set of vehicles is denoted as V= {1, 2, …, |V|} and indexed by *v*. Each vehicle has a capacity D_v (unlike Dumas et al. (1991), here the vehicles are heterogeneous with different capacities).

For each *i*,*j* ϵ *N* (*i*≠*j*) and *v* ϵ *V*, t_{ijv} is the travel time to traverse link *ij* using vehicle *v*. The travel times are outputs from Google Maps Directions Application Programming Interface (API) (*20*). It is not necessary for $t_{ijv} = t_{jiv}$. Traffic conditions were not considered; we used Google Maps API's default of "best guess" travel time estimates. They are based on historical averages and live traffic when the travel times are calculated (Developer Guide-Google). Additionally, it is assumed that the travel times to traverse a link using one vehicle is the same as using another vehicle, $t_{ijv} = t_{ijk}\,; \forall v, k \in V, v \neq k$. In contrast, Feng et al. (2017) uses Network Analyst Toolbox in ArcGIS to compute travel times, which is based on the shortest distance and speed limits. Since Google Maps Directions estimates travel times differently from Network Analyst in ArcGIS, the estimated travel time for a common origin and destination pair may not be the same. Yet both methods may also result in the incorrect travel times. Vodopivec et al. (2015) and Madsen et al. (1995) consider stochastic travel times and allows for dynamic updating of traffic congestion, delays, road work, and vehicle breakdown.

Decision Variables

There are three different types of decision variables: flow variables $Xijv$; $\forall i, j \in N$ ($i \neq j$) and $v \in V$, time variables Ti; $\forall i \in P$ and Tov, $T_{2n+1,v}$; $\forall v \in V$, and load variables Yi; $\forall i \in P$. Each flow variable is binary and equals to 1 if link ij is traversed by vehicle v or 0 otherwise. Each time variable is non-negative and continuous (0-24). For example, 7:30 AM would be 7.5 and 7:30 PM would be 19.5. Tov is the time when vehicle v initially departs from the depot. Ti is the arrival time at node $i \in P$, and $T_{2n+1,v}$ is the arrival time of vehicle v back at the depot. To and T_{2n+1} are vehicle-specific whereas Ti's; $\forall i \in P$, are not, because all vehicles must originate and return to the depot, whereas each of the other pickup or delivery nodes (nodes $i \in P$) are visited only once and by exactly one vehicle. Load variables are non-negative and integers. They represent the number of persons in the vehicle just after leaving a node $i \in P$. Y's for the depots (Y_0 or Y_{2n+1}) are not decision variables since Y_0 is constrained to equal 0, and Y_{2n+1} does not exist as no vehicle ever leaves the last depot. These load variables are also not vehicle-specific because each of the other pickup or delivery nodes (nodes $i \in P$) are visited only once and by exactly one vehicle.

PDPTWCC formulation

Min $\sum_{v\epsilon V} \sum_{i\epsilon N} \sum_{j\epsilon N} (t_{ijv} \cdot X_{ijv}) + \sum_{v\epsilon V} (T_{2n+1,v} - T_{0v})\,; i \neq j$ (1)

$\sum_{v\epsilon V} \sum_{j\epsilon N} (X_{ijv}) = 1;\ \forall i \in P^{+}; i \neq j$ (2)

$\sum_{j\epsilon N} (X_{ijv}) - \sum_{j\epsilon N} (X_{jiv}) = 0;\ \forall i \in P;\ \forall v \in V; i \neq j$ (3)

$\sum_{j\epsilon P^{+}} (X_{0jv}) = 1;\ \forall v \in V$ (4)

$\sum_{i\epsilon P^{-}} (X_{i,2n+1,v}) = 1;\ \forall v \in V$ (5)

$\sum_{j\epsilon N} (X_{ijv}) - \sum_{j\epsilon N} (X_{j,n+i,v}) = 0;\ \forall i \in P^{+}, \forall v \in V; i \neq j$ (6)

$\sum_{v\epsilon V} \sum_{j\epsilon P^{-}} (X_{0jv}) = 0$ (7)

$\sum_{v\epsilon V} \sum_{i\epsilon N} (X_{i0v}) = 0$ (8)

$\sum_{v\epsilon V}\sum_{i\epsilon P^+}(X_{i,2n+1,v})= 0$ (9)

$\sum_{v\epsilon V}\sum_{j\epsilon N}(X_{2n+1,j,v})= 0$ (10)

$X_{ijv}=1 \rightarrow T_i + t_{ijv} \leq T_j;\ \forall i,j \epsilon P, v \epsilon V; i \neq j$ (11)

$X_{0jv}=1 \rightarrow T_{0,v} + t_{0jv} \leq T_j;\ \forall j \epsilon P^+, v \epsilon V$ (12)

$X_{i,2n+1,jv}=1 \rightarrow T_i + t_{i,2n+1,v} \leq T_{2n+1,v};\ \forall i \epsilon P^-, v \epsilon V$ (13)

$a_i \leq T_i \leq b_i;\ \forall i \epsilon P$ (14)

$a_0 \leq T_{0,v} \leq b_0$ (15)

$a_{2n+1} \leq T_{2n+1,v} \leq b_{2n+1}$ (16)

$X_{ijv}=1 \rightarrow T_i + t_{i,n+i,v} \leq T_{n+i};\ \forall i,j \epsilon P^+, v \epsilon V; i \neq j$ (17)

$X_{ijv}=1 \rightarrow Y_i + d_j = Y_j;\ \forall i \epsilon P, j \epsilon P^+, v \epsilon V; i \neq j$ (18)

$X_{ijv}=1 \rightarrow Y_i - d_{j-n} = Y_j;\ \forall i \epsilon P, j \epsilon P^-, v \epsilon V; i \neq j$ (19)

$X_{0jv}=1 \rightarrow Y_{0v} + d_j = Y_j;\ \forall j \epsilon P^+, v \epsilon V$ (20)

$0 \leq Y_i;\ \forall i \epsilon P^+$ (21)

$X_{ijv} = 1 \rightarrow Y_j \leq D_v;\ \forall i \epsilon P, j \epsilon P^+, v \epsilon V$ (22)

$Y_{ov} = 0; v \epsilon V$ (23)

The optimization seeks to minimize the objective function, (1), which is the sum of the total travel cost (travel time) to fulfil all the requests and the total travel time the vehicles are out of the depot. In Dumas et al. (1991), the objective function differs from this one since it does not include the total travel time the vehicles are out of the depot. The first constraint, (2), restrict each pickup to have one and only one path. The second constraint, (3), assures that no pick-up or drop-off node is revisited. (4-5) restricts one and only path leading from or to depot. (6) ensures each drop-off trip to be on the same path as its pick-up. (7-10) rule out illogical flows (i.e. flow from the originating depot directly to a drop-off location, flow from any nodes to the originating depot, flow from a pick-up location directly to the last depot, and flow from the last depot to any other nodes).

(11-17) are temporal constraints to ensure that departure and arrival times are in sensible orders and within the time windows. (11) restricts the arrival time at a pick-up or delivery node *j* (*Tj*), to be no sooner than the time of arrival at pick-up or delivery node *i* (*Ti)* plus the travel time from node *i* to *j* (t_{ij}), if there is flow from node i to j. Similarly, (12) restricts the arrival time at pick-up node j (*Tj*) to be no sooner than the departure time at the originating node ($T_{o,v}$) plus the travel time from node *0* to *j* (t_{0jv}), if there is flow from node 0 to j. Meanwhile, (13) restricts the arrival time at the last depot, $T_{2n+1,v}$, to be no sooner than the arrival time at the drop-off node *i* (*Ti*) plus the travel time from node *i* to *2n+1* ($t_{i,2n+1}$), if there is flow from node *i* to $2n+1$. (14-16) ensure departure times (from originating node) and arrival times (at all other nodes) are within their corresponding time windows. Lastly, (17) restricts the arrival time at a delivery node *n+i* (T_{n+i}), to be no sooner than the time of arrival at pick-up node *i* (*Ti)* plus the travel time from node *i* to *n+i* ($t_{i,n+i}$). This ensures the start time of a pick-up to be before the start time of its drop-off.

(18-23) are loading and capacity constraints. (18-20) ensure that at pickup locations, the number of people picked up are added to the existing load in the vehicle, while at delivery locations, the number of people delivered are subtracted from the load in the vehicle. (18) restricts the number of passengers in the vehicle after leaving pick-up node *j* (Y_j) to be exactly the load in the vehicle after leaving pick-up or delivery node *i* (Y_i) plus the number of passengers picked up at node *j*, if there is flow from node *i* to node *j* on vehicle *v*. If *i* is a pick-up node, then customer *i* does not directly go to its drop-off location but instead pools with customer *j*. (19) restricts the load in the vehicle after leaving delivery node *j* (Y_j) to be exactly the number of passengers in the vehicle after leaving pick-up or delivery node *i* (Y_i) minus the number of passengers delivered to node *j*, if there is flow from node *i* to *j* on vehicle *v*. Similarly, (20)

restricts the number of passengers in the vehicle after leaving pick-up node *j* (Y_j) to be exactly the load in vehicle *v* after leaving the originating depot node *0* (Y_{0v}) plus the number of passengers picked up at node j, if there is flow from node *0* to *j* on vehicle *v*. (21) assures that the load or number of people in the vehicle after leaving any pick-up node is never negative. (22) bounds the load or number of people in the vehicle after leaving any pick-up node to be no more than the capacity of the vehicle v, if there is flow from node *i* to *j* on vehicle *v*. Finally, (23) assumes each vehicle was empty after it leaves the originating depot.

Time Windows

The bounds for the commence times $T_k;\ \forall k \in P$ are also determined based on data from the passenger survey. It was assumed that the time stamp in the passenger survey for each passenger is the latest that they can arrive at the airport (arrival time's upper bound or b_i). This is actually the time that they took the survey. Unfortunately, the information on when the passengers arrive at the airport or their flight times was not available. The lower bound of the arrival time (a_i) is 10 minutes prior to the upper bound (or $b_i - 10\text{ min} * \frac{1\text{ hour}}{60\text{ min}}$). This means 10 minutes short of the upper bound is the earliest that the passenger can be delivered. Together, b_i and a_i are the bounds of $T_i;\ \forall i \in P^-$. To get the bounds of $T_j;\ \forall j \in P^+$, the direct travel time to serve that request is subtracted from the corresponding arrival bounds. For example, b_j, the upper bound of $T_j;\ \forall j \in P^+$ is $= b_i$- t_{ij}. Similarly, a_j, the lower bound of $T_j;\ \forall j \in P^+$ is $= a_i$- t_{ij}.

6.3 Airport Access Requests of Air Passengers Traveling Alone

All the requests are ordered by ascending latest arrival times ($b_i's$) . Following sorting, they are then divided into groups of six requests. With a total of 318 requests, there were 53 optimization problems to solve. Again, the problems were solved using the Gurobi Optimizer.

An example of one of the problems with 6 requests is shown below (Table 6.1). The requests are numbered 1-6 respectively. They require pick-ups from the following respective zip codes: 90045, 92008, 93536, 90245,91722, and 91601. The latest that the passengers can arrive at LAX are respectively, 7:23 AM, 7:24 AM, 7:27 AM, 7:28 AM, 7:30 AM, and 7:32 AM. The direct travel times from the pick-up location to LAX are respectively, 5 minutes, 91 minutes, 78 minutes, 11 minutes, 51 minutes, and 35 minutes. Pick-up nodes are 1-6 respectively and delivery nodes are 7-12 respectively. With these inputs, one can determine the lower bound of the arrival time, and the lower and upper bounds of the departure time.

Table 6.1. Example of a PDPTWCC Problem

	Pick-Up				Delivery				
Req. No.	**Node $i \in P^+$**	**Location Zip Code (City)**	**Departure Time Upper Bound, b_i $i \in P^+$**	**Departure Time Lower Bound, $a_i, i \in P^+$**	**Node $j \in P^+$**	**Location**	**Arrival Time Upper Bound, b_j $j \in P^-$**	**Arrival Time Lower Bound, $a_i, j \in P^-$**	**Direct travel time, t_{ij}**
1	1	90045 (Los Angeles)	7.3 (or 7:18 AM)	7.133333 (or 7:08 AM)	7	LAX	7.383333 (or 7:23 AM)	7.216667 (or 7:13 AM)	0.083333 (or 5 min.)
2	2	92008 (Carlsbad)	5.883333 (or 5:53 AM)	5.716667 (or 5:43 AM)	8	LAX	7.4 (or 7:24 AM)	7.233333 (or 7:14 AM)	1.516667 (or 91 min.)
3	3	93536 (Lancaster)	6.15 (or 6:09 AM)	5.983333 (or 6:05 AM)	9	LAX	7.45 (or 7:27 AM)	7.283333 (or 7:17 AM)	1.3 (or 78 min.)
4	4	90245 (El Segundo)	7.283333 (or 7:17 AM)	7.116667 (or 7:07 AM)	10	LAX	7.466667 (or 7:28 AM)	7.3 (or 7:18 AM)	0.183333 (or 11 min.)
5	5	91722 (Covina)	6.65 (or 6:39 AM)	6.483333 (or 6:29 AM)	11	LAX	7.5 (or 7:30 AM)	7.333333 (or 7:20 AM)	0.85 (or 51 min.)
6	6	91601 (Los Angeles)	6.95 (or 6:57 AM)	6.783333 (or 6:47 AM)	12	LAX	7.533333 (or 7:32 AM)	7.366667 (or 7:22 AM)	0.583333 (or 35 min.)

There are two other nodes in addition to the 12 nodes we previously mentioned. These two nodes resemble the starting and last depot. Both the starting and final depot are set as Lot C, which is an off-site, nearby public parking lot. This lot is located about 0.7 miles away from LAX, on 96th St. & Sepulveda Boulevard, Los Angeles, CA 90045. Service may start as early as 3:00 AM but must conclude no later than 2:00 AM the following day.

6.4 Application of Pick-Up and Delivery Problem with Time Windows and Capacity Constraints

We attempt to pool the six passengers in four vehicles. If a solution is found, there would be a reduction of two trips because of pooling. The vehicles may have different capacities. In this problem, two vehicles each have capacities of 4 passengers, while the other two vehicles each have capacities of 5 passengers. An optimal solution was found, and it is shown on Table 6.2 below. Note that only nonzero decision variables are listed.

Table 6.2. Solution to the Example Problem

Flow Variables, $X_{i,j,v}$	**Time Variables, $T_{0,v}$, $T_{2n+1,v}$, or T_i**	**Load Variables, Y_i**
$X_{0,2,1}$=1	$T_{0,1}$=4.23333 (or 4:14 AM)	Y_1=2
$X_{2,4,1}$=1	$T_{13,1}$=7.48333 (or 7:29 AM)	Y_2=1
$X_{4,10,1}$=1	$T_{0,2}$=4.65 (or 4:39 AM)	Y_3=1
$X_{8,13,1}$=1	$T_{13,2}$=7.46667 (or 7:28AM)	Y_4=2
$X_{10,8,1}$=1	$T_{0,3}$=5.83333 (or 5:50 AM)	Y_5=1
$X_{0,3,2}$=1	$T_{13,3}$=7.58333 (or 7:35 AM)	Y_6=1
$X_{1,7,2}$=1	$T_{0,4}$=6.33333 (or 6:20 AM)	
$X_{3,1,2}$=1	$T_{13,4}$=7.61667 (or 7:37 AM)	
$X_{7,9,2}$=1	T_1=7.3 (or 7:18 AM)	
$X_{9,13,2}$=1	T_2=5.71667 (or 5:43 AM)	
$X_{0.5.3}$=1	T_3=6 (or 6:00 AM)	
$X_{5,11,3}$=1	T_4=7.21667 (or 7:13 AM)	
$X_{11,13,3}$=1	T_5=6.65 (or 6:39 AM)	
$X_{0,6,4}$=1	T_6=6.95 (or 6:57 AM)	
$X_{6,12,4}$=1	T_7=7.38333 (or 7:23 AM)	
$X_{12,13,4}$=1	T_8=7.4 (or 7:24AM)	
	T_9=7.38333 (or 7:23 AM)	
	T_{10}=7.4 (or 7:24 AM)	
	T_{11}=7.5 (or 7:30 AM)	
	T_{12}=7.53333 (or 7:32 AM)	

The first vehicle starts its service and leaves the depot at 4:14 AM. There are no passengers in the car upon leaving node 0. It serves the second and fourth request. It arrives at pickup node 2 at 5:43 AM. Now, there is a passenger in the car upon leaving node 2. It then picks up another passenger at node 4 and arrives at node 4 at 7:13 AM. Then there are two passengers in the vehicle upon leaving node 4. Requests 2 and 4 are pooled. They arrive at LAX (nodes 10 and 8) at 7:24 AM and the two passengers are delivered. Upon leaving LAX, the vehicle is again empty. It then returns to the depot and arrives at 7:29 AM.

The second vehicle starts its service and leaves the depot at 4:39 AM. There are no passengers in the car upon leaving node 0. This vehicle serves the first and third request. It first picks up the third request and arrives at pickup node 3 at 6:00 AM. There is a passenger in the car upon leaving node 3. Then it picks up another passenger at node 1 and arrives at node 1 at 7:18 AM. There are two passengers in the vehicle upon leaving node 1. Requests 1 and 3 are pooled. They arrive at LAX (nodes 7 and 9) at 7:23 AM and the two passengers are delivered. Upon leaving LAX, the vehicle is again empty. It then returns to the depot and arrives at 7:28 AM

The third vehicle starts its service and leaves the depot at 5:50 AM. There are no passengers in the car upon leaving node 0. This vehicle serves only one request, the fifth request. It arrives at pick-up node 5 at 6:39 AM. There is a passenger in the car upon leaving node 5. It arrives at LAX (node 11) at 7:30 AM and the single passenger is delivered. Upon leaving LAX, the vehicle is again empty. It returns to the depot and arrives at 7:35 AM.

The last vehicle starts its service and leaves the depot at 6:20 AM. There are no passengers in the car upon leaving node 0. This vehicle serves only one request, request number 6. It arrives at pick-up node 6 at 6:57 AM. There is a passenger in the car upon leaving node 6. It

arrives at LAX (node 12) at 7:32 AM and the single passenger is delivered. Upon leaving LAX, the vehicle has no passengers. It returns to the depot and arrives at 7:37 AM.

6.5 Number of Trips Saved with Pooled Service

Then we ran the 53 optimization problems for all 318 passengers or requests. On Table 6.3, we compared the number and percent of total matches and trips saved (reduction in trips) when the passengers are pooled using three, four, or five vehicles. When using just three vehicles for each group of 6 requests, no optimal solution was found in all 53 cases. Perhaps limiting the detour to be no more than 10 minutes and restricting that every 2 parties are pooled in one vehicle, is too constricting. Since no optimal solution was found, no trips were saved. Increasing the number of vehicles would increase the possibility of matches but reduce the number of trips saved per match. When using 4 vehicles for each batch of 6 requests, an optimal solution was found 14 times of the 53 cases (26.4%). For each match, the total number of 318 trips is reduced by 2 trips. The total number of trips saved in this case is 28 (8.8% reduction in number of trips). Using five vehicles results in the highest number of matches and trips saved. An optimal solution was found 36 times of the 53 cases (67.9%). For each match, the total number of 318 trips is reduced by 1 trip. The total number of trips saved is 36 (11.3% reduction in number of trips).

Table 6.3. Number and Percent of Total Matches and Trips Saved

	3 vehicles	4 vehicles	5 vehicles
Total Number of Matches or Occurrences when an Optimal Solution was Found (n=53)	0	14	36
Number of Trips Saved per Match	3	2	1
Total Number of Trips Saved (n=318)	0	28	36
Matching Rate (%)	0	26.4	67.9
Trips Saved (%)	0	8.8	11.3

Finally, we also ran the optimization with 6 vehicles (no pooling) and were able to find an optimal solution for all 53 cases. Even though the matching rate is 100%, since there is no

pooling, there is also no reduction in number of trips. The 100% matching rate was possible since the range in service times is very wide, and there is a vehicle to serve each of the request.

About 7.2 million passengers departed from LAX in July 2015 (Los Angeles World Airports- LAX Traffic Comparisons). According to the passenger survey, 54% of those passengers started their trip at LAX while 50% flew alone. Assuming those same shares, we estimate that nearly 73,000 passengers start their trip at LAX and fly alone each day. When 318 passengers participate in this program, the number of trips may be reduced by 36 trips or 11%. If all such passengers (starting their trip at LAX and flying alone) participated in this program, the service can reduce up to eight thousand trips each day. Fewer private trips to the airport would lessen the congestion on the airport curbside.

6.6.1 Conclusion

In order to alleviate congestion at the airport curbside, this study proposes an optimized, multi-passenger TNC service for people traveling to the airport. To more efficiently match and assign which passengers are pooled together, it applies the pickup and delivery problem. The shared ride service would add minimal increases in travel time. 318 requests of departing passengers starting their trip at Los Angeles International Airport (LAX) and flying alone, were formed based on data from the 2015 LAX Passenger Survey. The requests were then grouped by similar airport arrival times, prior to being optimized. Future work would consider more efficient heuristics to search for optimal solutions with large numbers of requests.

Our results suggest that there is potential to use shared ride services to reduce the number of cars and congestion at the airport curbside. We found that by pooling, we can decrease the number of trips by about 11%. If all departing passengers starting their trip at LAX and flying alone participated in this program, the service could cut up to 8000 trips daily. In addition to

access trips to the airport, extensions of this analysis can also include egress trips from the airport.

Chapter 7

Future Research

Extensions of this work, which will be conducted during my post-doctoral fellowship at Singapore Massachusetts Institute of Technology Alliance for Research and Technology (SMART), will continue to explore alternatives that maximize the potential of shared vehicles and focus on the issues of spatial and social inequalities in access at airports and other congested, non-airport locations in Singapore. Using the Future Mobility Sensing (FMS) data (activity travel survey data) that the SMART Future Urban Mobility Lab (FM) has collected, it will explore the current TNC market in Singapore. It will analyze who they serve and whether they increase access for minorities, women, seniors, passengers with disabilities. Using the same data, it will evaluate trips and optimal ways for TNCs to transition to their own autonomous vehicles to provide shared or pooled rides to improve mobility and access equity. Additionally, it will analyze the passenger demand, assuming minimal increases in travel time to pick-up and drop-off additional passengers. Some of the relevant questions are:

1. How large is the TNC market and who do they serve? (Analysis of FMS data). Specifically, do TNCs reduce or widen the disparities in access and mobility for low-income riders, racial minorities, women, and people living in or outside of central business districts? What is the share of TNC vehicles that are Americans with Disabilities Act (ADA)-accessible? Most vehicles are owned by ordinary people who drive for Uber or Lyft. How can the TNCs better integrate different vehicles (including ADA-accessible ones) as they transition to their own fleet of autonomous vehicles? The question of ADA-accessible vehicles and ADA trained drivers is of

key interest to many transit agencies. These agencies are developing or considering partnerships with TNCs to improve their service to rural areas and paratransit services.

2. How autonomous vehicles can be used to provide efficient, multi-passengers, Mobility-on-Demand (MOD) services? (Applications of Ridesharing and Matching Algorithms). If the public agency in Singapore were to roll out a fleet of autonomous TNC vehicles, what would it look like? What is its fleet size, vehicle types, assignments, and maximum detour? How can they better incorporate the frequency of on-demand requests (Poisson rate at which requests are made)? How can they prepare for the computation complexity? What is the total system time saved? Should it be door-to-door (like Uber, Lyft, and Grab) or non-door-to-door (like Via)? How can they better rebalance popular vs. less popular locations? Finally, Singapore has a vehicle quota system. Should the bidding of certificate of entitlement for TNC vehicles be in the same category as those for other private vehicles?

3. What would be the passenger demand? (Travel Demand Models). After setting up the ridesharing algorithm with our allotted maximum detour, how would passengers react to these changes? Which would take a shared mode, a pooled TNC? How can they better design pricing or fares, and or service quality, based on cost and or travel time elasticities. Other characteristics of shared rides include convenience and service accessibility. For example, families traveling with children might not have car seats, and some passengers with disabilities need ramps and wheelchair accessible vehicles. How can they address these concerns? We will return to studying the impact on other modes (substitution and complementary effects) and travel behavior.

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