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Improving Productivity and Accessibility of Transit Systems with On-demand and Shared TNCs in Low Demand Areas

DISSERTATION

submitted in partial satisfaction of the requirements
for the degree of

DOCTOR OF PHILOSOPHY

in Civil and Environmental Engineering

by

Negin Shariat

Dissertation Committee:
Professor R. Jayakrishnan, Chair
Professor Stephen Ritchie
Associate Professor Michael F. Hyland

2025

Chapter 4 and Portions of Chapters 1, 5, and 6 © 2025 Elsevier
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DEDICATION

To

My husband, Dr. Mahdi Khodayar, whose unwavering support, patience, and encouragement have been my greatest strength throughout this journey.

To

My beloved parents, Maryam Tamimi and Masoudreza Shariat,
and my dear sister Nasim Shariat, for their endless love, faith, and encouragement that have guided me every step of the way.

TABLE OF CONTENTS

Page

LIST OF FIGURES vi

LIST OF TABLES viii

ACKNOWLEDGMENTS ix

VITA xi

ABSTRACT OF THE DISSERTATION xii

CHAPTER 1: Introduction 1

CHAPTER 2: Literature Review 10

2.1. Conceptual Foundations and Emerging Mobility Models 10

2.2. Adoption, Users, and Demographic Patterns 11

2.3. Competition, Complementarity, and Impacts on Transit 12

2.4. System-Level Externalities: Congestion, Environment, and Equity 13

2.5. Flexible and Semi-Flexible Transit Models 15

2.6. Governance Frameworks and Analytical Evaluations 17

2.7. Algorithm for Integrated Mobility and Ride-sharing 18

CHAPTER 3: Stop-level Shared TNC Service with Heuristic Ride Matching 20

3.1. Route Analysis Approach 21

3.2. Selecting Candidate Routes/Segments for Truncation 25

3.3. TNC Substitution Algorithm 28

3.4. Contractual Structures 33

3.5. Numerical Result: 35

3.6. Candidate Selection 38

3.7. Summary of Heuristic TNC Ride-matching 43

CHAPTER 4: Door-level Shared TNC Service with PDPTW Solution 45
4.1. Framework 50
4.2. Generating Passenger ODs 52
4.3. Estimating TNC Operation Time/Distance and Cost 53
4.4. Numerical Case Study in the City of Long Beach 60
4.5. TNC Compensation Contract and Bus Cost 62
4.6. Cost Savings from TNC Substitution 68
4.7. Passenger Disutility 71
CHAPTER 5: Comparison of Different Service Designs 75
5.1. TNC Operation in Low-demand Segments in the Middle of the Route . 76
5.2. Parallel TNC Service vs Combined Operation on Neighboring Routes . 77
5.3. Effect of Bus Frequency 80
5.4. Effect of Bus Stop Density 82
5.5. Stop-level TNC Service 84
5.6. Non-cooperative Scenario between Transit Agencies and TNCs 86
5.7. Demand Responsive Transit (DRT) versus TNC as a Substitution 89
CHAPTER 6: Analysis of Influencing Factors 92
6.1. Regression 94
6.2. Correlation 96
6.3. Bivariate Analysis 98
CHAPTER 7: Real-world Cases, Takeaways, Challenges and Benefits 102
7.1. Real-world Partnership Example 103
7.2. Transit Agency Interviews and Insights 106
7.3. Challenges, Solutions, and Benefits of Transit–TNC Partnerships 111

CHAPTER 8: Conclusions 121

BIBLIOGRAPHY 127

APPENDIX 136

LIST OF FIGURES

Page

Figure 1-1: Transit trips per capita since 2009 (Manville et al., 2018) 2

Figure 1-2 : Weekly transit ridership from March 2018 to the end of August 2025 3

Figure 3-1 : Long Beach Bus network with 21

Figure 3-2 : Tulsa, Ok, Bus network with downtown specified 22

Figure 3-3 : Bus and TNCs' operation before and after the truncation point 25

Figure 3-4: Example of TNC Passengers grouping by ranking heuristic 32

Figure 3-5: Route 91Stops where the criteria are met 38

Figure 3-6: Route 93 Stops and suggested Candidates in Early Morning 39

Figure 3-7: (a) VMT and (b) VHT of TNCs (with passenger) Total saved buses' (c) VMT and (d) VHT, (e) Minimum number of needed TNC vehicles 41

Figure 3-8: (a) Estimated cost for the suggested contract types, (b) Saved cost of not using the buses for the TNC-substituted segments 41

Figure 4-1: Operation of buses and TNCs after the truncation points 47

Figure 4-2: Modelling and decision framework 51

Figure 4-3: Generating transit passenger ODs 53

Figure 4-4: Example of m-PDPTW 54

Figure 4-5: Long Beach Transit Stops and Examples of Truncation Candidates 62

Figure 4-6: Comparison of Contract Types 65

Figure 4-7: Comparison among Different TNC Share Percentages ($\beta\ from\ 0.2\ to\ 0.7$). 67

Figure 4-8: Cost and savings of TNC substitution for selected routes 70

Figure 4-9: Passenger Disutility Comparison 74

Figure 5-1: TNC operation in the truncated intermediate segments 76

Figure 5-2: Routes 91,92, and 93 Long Beach transit 78

Figure 5-3: Example route with 2 different bus frequencies 80

Figure 5-4: Example route with 2 different bus stop densities 82

Figure 5-5: Cost and Passenger Disutility (Door-level versus Stop-level) 86

Figure 5-6: Cost and Passenger Disutility of TNCs Contracted vs Uncontracted Service 88

Figure 5-7: Cost and Passenger Disutility under Different Services 91

Figure 6-1: Heatmap of correlations across all factors 97

Figure 6-2: Bus, TNC cost and Total Savings versus Multiple Factors 100

LIST OF TABLES

Page

Table 3-1 : Summary of sequences of bus and TNCs movements 24

Table 3-2: LBT routes saving after truncation and substitution in early AM 37

Table 4-1: TNC Compensation Schemes 63

Table 5-1: Comparison of individual route operation vs. combined operation 79

Table 5-2: Comparison of 2 scenarios with different frequencies 82

Table 5-3: Comparison of 2 scenarios with different stop densities 84

Table 6-1: Key Factors/Metrics in a Truncated Segment 92

Table 6-2: Summary of top regression models to predict total saving 95

Table 7-1: Examples of recent partnerships of transit agencies and TNCs 103

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During the preparation of this work AI (ChatGPT) was used in order to check grammar, reduce typos and improve readability. After using this tool, the authors reviewed and edited the content as needed and would take full responsibility for the content.

The future of transit is not a single mode.
The future of transit is a strategy.

VITA

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ABSTRACT OF THE DISSERTATION

Improving Productivity and Accessibility of Transit Systems with
On-demand and Shared TNCs in Low-Demand Areas

by
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Doctor of Philosophy in Civil and Environmental Engineering
University of California, Irvine, 2025
Professor R. Jayakrishnan, Chair

Public transit agencies exist to provide equitable access to travel. This mission often requires operating full-size buses or trains during times and in areas with very low demand, resulting in unnecessarily high operating costs. Meanwhile, app-based transportation network companies (TNCs) offer flexible, on-demand, point-to-point service. This research evaluates whether, and under what conditions, transit agencies can replace low-productivity bus segments with TNC services without any worsening of access equity.

This study develops a three-stage decision framework to: (1) identify low-demand segments using a stop-level screening method, (2) assess operational feasibility and cost-effectiveness of point-to-point TNC service through an optimization model based on a multi-vehicle pickup-and-delivery problem with time windows (by presenting possible contractual structures for the partnership), and (3) create predictive tools that estimate potential for TNC substitution of transit without running the computationally expensive optimization model. Results from a Long Beach Transit case study show that service-segment truncation, such as with short-turning of transit vehicles and TNC substitution for the remaining line segment, can reduce operating costs by up to 60% while improving passenger utility by approximately 50%.

The proposed optimization formulation is flexible and can be applied to different spatial demand patterns, varying frequency, passenger density, and coordinated TNC substitution on multiple routes. The framework can also be used for other comparable service options, such as stop-to-stop TNC pickup, individually subsidized rides, and demand-responsive shuttles as well as for comparisons against the proposed door-level (curb to curb) service. Regression models and bivariate correlations identify key criteria that help agencies determine when segment truncation and TNC substitution are likely to succeed. Transit agencies operating under different network geometries and demand conditions can use the framework as a practical, step-by-step method to assess TNC substitution and to manage the process from initial contracting to piloting and full-scale operation.

Real-world pilots in Dallas, Los Angeles, and Pinellas County confirm that TNC substitution preserves access when agencies maintain control over fare integration, incentives, and service rules through clear contracting. The purpose here is not to advocate TNC substitution as a way to reduce transit service; rather, TNC substitution enables agencies to reallocate resources. Such reallocation, as in the case of short-turning of transit service considered here, can increase the frequency on the segments served by transit, which in turn can conceivably induce more demand as well. Transit operations can then be more focused on the segments where demand is highest, with TNC operations continuing to give the same level of service in the less-productive segments. As induced demand from such reallocation is not studied herein, the estimated benefits of TNC-substitution in this research can be considered conservative.

CHAPTER 1: Introduction

Public transit is one of the most important shared assets of an urban region, enabling access to jobs, education, health care, and essential services for people who cannot or prefer not to rely on private automobiles. Public transit agencies have long sought to work with the private sector in various forms of partnership to enhance service provision, with varying levels of success. These partnerships often aim to improve the efficiency of fixed-schedule public transit, particularly in areas where private operators can offer more flexible routes and schedules and be cost-effective.

In recent years, the emergence and rapid expansion of Transportation Network Companies (TNCs) such as Uber and Lyft have provided transit agencies with new opportunities for collaboration (Shaheen & Cohen, 2020). Leveraging digital platforms, these companies offer real-time, on-demand ride-hailing and ridesharing services, fundamentally reshaping mobility options in cities. While TNCs have typically been considered in the context of solving first-mile/last-mile (FMLM) challenges in areas with poor transit accessibility, especially for low-wage workers (Mass Transit, 2019) , they also open up new possibilities for addressing broader transit system inefficiencies. A Transportation Cooperative Research Program (TCRP) report (Board & National Academies of Sciences and Medicine, 2019) has provided practical guidance to decision-makers on the conditions under which such partnerships may be beneficial. Nonetheless, there remains considerable room for further operational enhancements that can maximize the productivity and accessibility gains from transit-TNC integration. This dissertation is motivated by these opportunities.

In the United States, public transit has faced long-term ridership challenges. Over the past half-century, transit ridership has significantly declined when accounting for overall

population and employment growth, despite some temporary gains in certain decades and exceptions in select cities such as Los Angeles and San Francisco that outperformed many rust-belt regions (Yonah Freemark, 2021). Unfortunately, in California, and especially in the Southern California Association of Governments (SCAG) region, ridership has been on a notable downward trend during the past fifteen years. Figure 1-1 shows this decline by illustrating transit trips per capita since 2009.

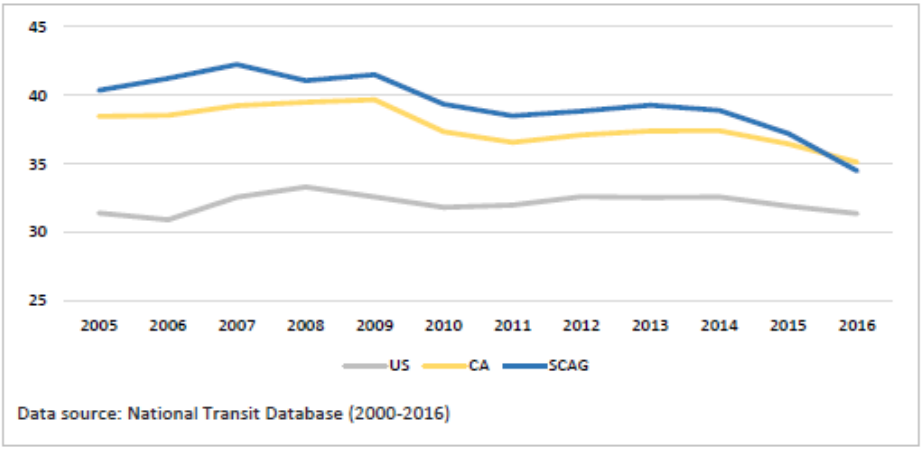


Figure 1-1: Transit trips per capita since 2009 (Manville et al., 2018)

The COVID-19 pandemic further exacerbated this problem. In April 2020, national transit ridership dropped to historic lows. Using data from the American Public Transportation Association (APTA, 2025), Figure 1-2 illustrates the weekly ridership levels for the period from early April 2018 through the end of August 2025. While there has been recovery since the lowest point, national ridership levels remain at around 80% of their pre-pandemic baseline. Public transit systems operate services in areas with low ridership as well, for equitable access reasons. The ridership losses from COVID-19 have only exacerbated concerns that there are now even more low-ridership (and thus less productive and profitable) service segments in existing lines.

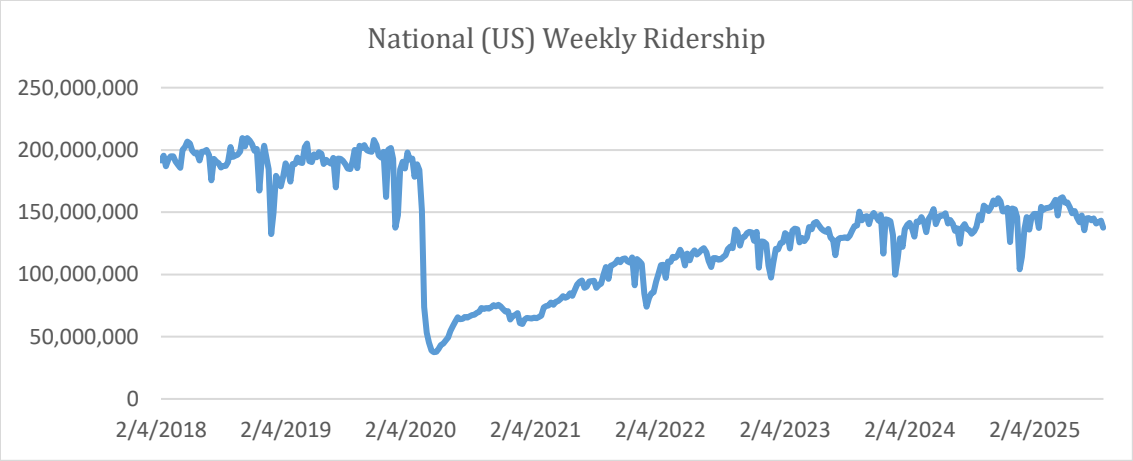


Figure 1-2 : Weekly transit ridership from March 2018 to the end of August 2025

The ridership trend underscores a fundamental challenge facing transit agencies: how to maintain high-quality and equitable service in low-demand areas or off-peak periods while ensuring financial sustainability. Transit demand is highly variable across space and time. In suburban or peripheral zones, as well as during early morning and late-night periods, ridership is often extremely low (Murphy et al., 2022). Operating full-sized buses, given high driver and fuel costs in such contexts, is highly unproductive. Yet, eliminating services altogether risks creating accessibility and equity problems, as many commuters, including essential and low-income workers, depend on transit as their only mobility option. Agencies are therefore caught in a trade-off between maintaining a normal headway to guarantee service quality and reducing frequency or coverage to control costs.

The advent of TNCs provides a potential solution. By crowdsourcing mobility supply from the general public and deploying dynamic, app-based routing and dispatching, TNCs can offer cost-effective, on-demand service. For transit agencies, integrating TNCs into service delivery holds the promise of simultaneously addressing low-productivity bus operations and maintaining equitable access (Lucken et al., 2019). While concerns have been

raised about the possible negative impacts of TNCs, such as reductions in traditional transit ridership or induced demand for private trips (Malalgoda & Lim, 2019; Erhardt et al., 2022; Rayle et al., 2016), and results from pilot studies have reduced the enthusiasm for public-private partnerships to improve transit outcomes, well-designed partnerships with TNCs still hold promise.

In practice, public-private partnerships between transit agencies and TNCs can take several forms. Lucken et al., 2019 categorize them into four major types: First Mile/Last Mile (FMLM), low-demand density, off-peak, and paratransit services. These categories are not mutually exclusive, and an agency might choose to partner with TNC for multiple purposes. Nevertheless, most implemented partnerships to date have focused on FMLM problems, whereas solutions specifically targeting low-demand areas or off-peak periods remain underexplored in both research and practice. This gap is central to the motivation for this dissertation, which focuses on the potential of transit-TNC partnerships to enhance productivity and accessibility in low-demand contexts.

Previous studies have explored various aspects of the integration and partnerships between transit agencies and TNCs. The most frequently examined one is leveraging TNCs and ridesharing as an FMLM solution for transit systems (Nam et al. 2018; Grahn et al., 2020; Zhu et al., 2020; Grahn et al., 2021; Kumar & Khani, 2021; Nickkar et al., 2022). In this category of research, various optimization methods have been applied to minimize total cost or maximize the efficiency (e.g., transit ridership) of the integrated system. Other studies on the transit-TNC public-private partnership (PPP) include analyzing the characteristics of transit-TNC service users (Grahn et al., 2020; Grahn, Qian, Matthews, et al., 2021; Khatun & Saphores, 2022), improving job accessibility with the transit-TNC service (Hu & Sun, 2023),

leveraging the service for transit-disadvantaged populations (Steiner et al., 2021), and evaluating the impact of the transit-TNC service on transit ridership (Zuniga-Garcia et al., 2022).

However, significantly fewer studies have examined TNCs as a substitute for fixed-route transit during low-demand periods or in low-demand areas. When agencies consider TNCs as a low-demand solution, two strategies typically emerge. The first is to operate both fixed-route buses and TNC services in parallel, subsidizing both heavily, a model that risks long-term financial unsustainability. The second is to replace fixed-route service with TNCs in selected segments or periods. Despite its promise, this substitution approach has not been sufficiently studied, creating an important research gap.

The motivation for this research also stems from specific observations of the Long Beach Transit system in Long Beach, CA. Stop-level ridership analysis in 2019 and 2020 reveals that certain peripheral segments of LBT routes suffer from particularly low passenger volumes, especially at the beginning or end of lines, and during off-peak periods (Murphy et al., 2022). For example, early-morning and late-night services often carry very few passengers in these segments, while buses still incur the full costs of operation. This misalignment between resource allocation and demand highlights the need for cost-effective alternatives. Substituting TNC vehicles for buses in these contexts could generate cost savings due to their smaller size and significantly lower purchase cost, while preserving accessibility for the few travelers who rely on these services. Passengers could board a TNC vehicle at their local bus stop/ pick up location at the scheduled time and transfer to the fixed-route bus at a truncation stop, maintaining a near-seamless (albeit with a transfer)

travel experience. Importantly, such substitution schemes must preserve at least the same service quality, including scheduled timing, to ensure equitable treatment of riders.

This dissertation builds on these ideas by developing and evaluating frameworks for substituting fixed-route bus segments with TNC services under conditions of low demand. The overarching objective is to provide transit agencies with practical and theoretically sound methods for improving system productivity while improving or preserving accessibility and equity. Chapter 2 provides a comprehensive review of the literature on the integration of public transit and TNCs, positioning these developments within the broader evolution of flexible and technology-enabled mobility systems. It synthesizes key findings on user behavior, governance, and system performance, highlighting both the opportunities and challenges of TNC–transit collaboration and its implications for accessibility, equity, and future mobility planning.

The research proceeds in two stages, corresponding to two papers that are integrated into this work. The first stage, which is presented in chapter 3, introduces a straightforward and intuitive framework for identifying unproductive bus segments, determining viable stops for service-truncation similar to traditional short-turning, and estimating the costs of substituting them with TNC services. The TNC services in this chapter are designed to operate by picking up and delivering passengers at existing transit stops, while preserving the level of service. This framework considers factors such as passenger counts, Vehicle Miles Traveled (VMT), Vehicle Hours Traveled (VHT), and cost savings from reduced bus operations. Because the TNC service operates only between transit stops, a simple passenger pooling scheme can be used to improve TNC operations.

The second stage presented in chapter 4 builds upon this, providing an area-wide TNC service by introducing a detailed optimization model, which formulates the TNC operations as a multi-vehicle pickup and delivery problem with time windows (m-PDPTW). The TNC service is to curbside at the origin points for passengers delivered to their transit stops and to curbside at the destination points for passengers picked up from their transit stops. This optimization model explicitly accounts for passenger demand patterns, TNC pooling possibilities, and alternative compensation structures for TNCs. Seven different cost structures are considered, ranging from fixed costs to compensation based on vehicle hours, service distances, and passenger numbers, providing guidance for transit agencies in contract negotiations.

Empirical validation of these frameworks is provided through a case study of the Long Beach Transit system in California. Using stop-level ridership and cost data, the study evaluates different bus route truncation and TNC-substitution scenarios. The analysis demonstrates potential savings from TNC substitution and quantifies the trade-offs for passengers, drivers, and the agency. By situating the research in a real-world urban transit system, the dissertation is practically relevant.

Building on the modeling results presented in Chapter 4, Chapter 5 provides a comparative assessment of the variations and flexibility of the proposed service design under different demand patterns and route ridership levels. This analysis aims to evaluate how effectively the proposed framework adapts to diverse operational contexts and how its performance changes with varying service characteristics. The chapter also compares the proposed design against several alternative approaches, including uncontracted TNC services, dedicated shuttle operations, and stop-level service adjustments. Through these

comparisons, it identifies the trade-offs among cost efficiency, service coverage, and operational simplicity. Ultimately, the chapter highlights the conditions under which the proposed substitution framework demonstrates superior outcomes and offers insights into its practical implementation for transit agencies.

Chapter 6 builds on this analysis by examining a range of factors that influence the practicality and effectiveness of substituting low-demand fixed-route segments with TNC services. These factors encompass both operational characteristics, such as demand distribution and ridership intensity, and system-level attributes that may determine whether a transit agency should adopt such substitution strategies. The chapter then develops several linear regression models and one non-linear model to explore how these factors relate to overall cost efficiency and service outcomes. Finally, the chapter investigates the relationships between each factor and key outcome measures such as TNC cost, bus cost savings, and total savings, to identify patterns that can guide agencies in determining where and under what conditions such partnerships are most beneficial.

Chapter 7 shifts the focus to an empirical examination of recent partnerships between transit agencies and TNCs across multiple U.S. cities, analyzing the objectives and types of services for which agencies engage TNCs to complement or enhance transit operations. The chapter then focuses on three representative case studies, drawing on interviews with key stakeholders to provide detailed insights into service design, operational implementation, and performance outcomes. It further explores both the realized benefits and the practical challenges encountered in these initiatives. By situating these empirical observations within the context of this study's analytical findings, the chapter underscores the relevance of the proposed framework and illustrates how it can offer structured guidance to address

operational, contractual, and planning challenges in real-world transit–TNC collaborations. Finally, Chapter 8 synthesizes the overall contributions of the dissertation, situating them within the broader discourse on transit productivity and accessibility, and offers recommendations for future research and practical implementation.

This dissertation makes four key contributions. First, it addresses a research gap by systematically analyzing the substitution of low-demand and off-peak fixed-route segments with TNC services, providing the first rigorous evaluation of this replacement strategy. Second, it develops frameworks for mutually beneficial transit–TNC partnerships that balance financial viability with service quality. These frameworks incorporate practical operational metrics that directly inform substitution feasibility. Third, it examines the design of TNC compensation models, an area that has received limited attention but is critical for ensuring financially sustainable partnerships. Finally, it investigates practical planning considerations and real-world experiences, including challenges and benefits that transit agencies can leverage when implementing such substitution strategies.

In summary, this dissertation is motivated by the pressing need for innovative solutions to the twin challenges of low transit productivity and declining ridership. By integrating TNCs into bus operations in low-demand contexts, transit agencies may reallocate scarce resources to higher-demand segments, improve overall productivity, and maintain equitable service for all riders. This work contributes to both academic research and practical policy discussions by developing decision-making frameworks, optimization models, and empirical insights that inform the design of financially sustainable and operationally feasible transit-TNC partnerships.

CHAPTER 2: Literature Review

2.1. Conceptual Foundations and Emerging Mobility Models

The emergence of TNCs is widely viewed as part of a broader transformation in urban mobility rather than an isolated development. A central question has been whether they would disrupt public transit or support integrated multimodal systems. Early research framed ride-hailing within the concept of Mobility-as-a-Service (MaaS), in which transit, shared mobility, and TNCs are bundled through unified planning and payment, providing policymakers and scholars with a framework for integration rather than competition. (Kamargianni et al., 2016). Clewlow and Mishra (2017) provided some of the earliest systematic evidence on how ride-hailing interacts with existing transit modes, using large-scale survey data across U.S. metropolitan regions. These regions include Boston, Chicago, Los Angeles, New York, San Francisco/Bay Area, Seattle, and Washington, D.C.. Their findings showed clear competition with buses and light rail, but a modest complementary effect for commuter and heavy rail, highlighting that the impacts are mode-specific rather than uniform. By documenting these subtle patterns, their study advanced the debate beyond speculation and established that ride-hailing could simultaneously undermine and support different parts of the transit network. Conway et al. (2018), using the National Household Travel Survey (NHTS), extended the conversation to national trends. They demonstrated that for-hire vehicle use doubled after ride-hailing's introduction. This was not a temporary disruption but a structural change. At the methodological level, Bertini (2003) demonstrated how archived bus operations data could be harnessed to evaluate transit performance. Although predating TNCs, this work anticipated the importance of operational data analytics that would later be applied to TNC–transit studies (Diao et al., 2021; Erhardt et al., 2022).

2.2. Adoption, Users, and Demographic Patterns

Beyond the question of disruption, researchers asked: who adopts TNCs, and what does this mean for transit? Early findings pointed to strong socio-demographic patterns that shaped both access and equity. Clewlow and Mishra (2017), also produced one of the first representative demographic profiles of ride-hailing adopters. They found that use was concentrated among younger, higher-income, and more educated urban residents, with adoption rates nearly an order of magnitude lower among older adults and disadvantaged populations. This classification raised early equity concerns, suggesting that the benefits of ride-hailing were unevenly distributed and shaped by access to technology, income, and geography. City-specific studies provided depth to these national observations. Grahn et al. (2020), using surveys in Pittsburgh, confirmed that income and education strongly predicted adoption, which only reinforced inequities. Gehrke et al. (2019) in Boston, highlighted substitution effects, showing that higher-income users often replaced walking or transit with TNCs. These results show that ride-hailing on its own might not be a good option to rely on for increasing accessibility, and probably benefits high-income groups more.

Other contexts revealed different barriers. Researchers in Birmingham, Alabama, emphasized perceptions of safety and cultural attitudes, showing that adoption is not only economic but also social (Sarjana et al., 2020). Some researchers focused on older adults and found that ride-hailing can be a supplement for this group (Tooley et al., 2019) with potential safety benefits. However, old age is associated with technology barriers (Currie & Delbosc, 2010). More recent studies emphasized that ride-hailing adoption is shaped not only by socioeconomic status but also by structural barriers, such as affordability, discrimination, service gaps, and digital literacy. Their review of prior evidence showed that low-income and

less-educated individuals are much less likely to use TNCs compared with higher-income households and people familiar with technology (Hu & Sun, 2023).

These studies indicate that without targeted policies, integrating TNCs into public transit risks reproducing inequities, since disadvantaged riders face both monetary and non-monetary obstacles to adoption. However, with planning, communication, and providing alternative options to resolve technological barriers, partnership with TNCs can benefit even the groups who couldn't previously utilize this new mobility.

2.3. Competition, Complementarity, and Impacts on Transit

Perhaps the most debated question is whether TNCs compete with or complement transit. The trajectory of research shows an evolution from early evidence of substitution to more layered recognition of context-dependent complementarity. Initial studies painted a clear picture of competition. Researchers showed that in San Francisco, TNCs drew riders away from buses. They usingd regression models, showed up to 12% declines in transit ridership to TNC entry (Erhardt et al., 2022). The results in (Diao et al., 2021), expanded the scale to 174 U.S. cities, confirming widespread bus losses, with the strongest impacts in bus-dominated systems. Dong et al. (2022), through surveys in Boston and Philadelphia, found that TNCs often substitute for transit while also delaying car ownership, with city-specific differences in how travelers perceive time costs between TNC and transit. Moreover, Dong (2020) added survey-based evidence from Philadelphia: more than 60% of users would have taken transit, mainly buses, if TNCs were unavailable. These studies formed an initial consensus: TNCs were bus competitors. Lee et al. (2022) showed that Uber's entry reshaped mode choices differently across traveler segments, with walkers and transit riders shifting to TNCs and overall congestion increasing, particularly in compact urban areas.

Yet, other studies complicated the story. Cats et al. (2022) found, through simulation modeling, that many TNC trips occurred in areas without viable transit alternatives, pointing to a complementary role. Deng et al. (2024) who analyzed real-time data from the Transit App, revealed that many TNC trips functioned as feeders to rail. Clewlow and Mishra (2017) showed a split: buses lost riders, but rail sometimes gained. Recent micro-level evidence by Giller et al. (2024) further clarified the conditions under which ride-hailing substitutes for or complements transit. Using detailed trip-level data, they identified that substitution effects dominate among short urban trips, whereas induced travel is more prevalent for medium-distance leisure journeys.

The research narrative, therefore, shifted from a simple substitution story to a dual narrative of competition and complementarity. The field now recognizes that impacts are not uniform but depend on mode, geography, and service design. Partnering with TNCs not only allows agencies to leverage them as a complementary service in areas of limited transit coverage but also produces a subsidized multimodal offering that is difficult for alternative providers to compete against.

2.4. System-Level Externalities: Congestion, Environment, and Equity

Once questions of adoption and ridership substitution were established, researchers began asking what ride-hailing meant for the wider transport system. Did TNCs reduce congestion by pooling trips, or worsen it by adding empty vehicle miles? Did they expand access equitably, or cluster only in wealthy areas? These system-level externalities became central to policy debates.

Erhardt et al. (2022) provided some of the most striking evidence. Using a calibrated traffic assignment model in San Francisco, they estimated that TNCs accounted for nearly

half of the congestion increase between 2010 and 2016, largely due to added vehicle miles traveled despite modest substitution effects. Millard-Ball et al. (2023) supported this view with GPS traces from Uber and Lyft vehicles, showing that more than 60% of TNC miles were deadheading (travel without passengers), leading to disproportionate congestion and emissions impacts. Environmental studies have added further complexity. Complementing the sustainability assessments, Martin et al. (2024) quantified the net VMT and greenhouse-gas effects of TNCs across U.S. metros, finding substantial added VMT and suggesting that while electrification may reduce emissions, induced demand could worsen congestion. More recently, Li and Vignon (2024) analyzed New York City's congestion surcharge using high-resolution trip records and found that although TNC volumes declined modestly, congestion remained largely unchanged due to shifts in trip timing and location. This underscores that pricing alone may be insufficient without complementary policies such as fleet caps or pooling incentives. Finally, Alsaleh and Farooq (2023) and Alsaleh et al. (2023) combined life-cycle analysis with simulation modeling, concluding that electrifying TNC fleets could reduce emissions by up to 98%, yet induced demand could offset these benefits, showing that technology alone cannot ensure sustainability.

These studies show that deploying TNCs without regulation can increase VMT, congestion, and emissions. Technological advances and electrification, while helpful, cannot fully resolve these impacts and only partially mitigate emissions. However, targeted deployment: focusing TNC use in appropriate areas, promoting effective pooling, and reducing deadheading through coordinated trip scheduling can offset these challenges and may even reduce emissions when replacing infrequent, inefficient bus service. Achieving these outcomes requires well-designed partnerships between transit agencies and TNCs.

Equity studies revealed a similarly divided picture. Barajas and Brown (2020) used spatial regression in Los Angeles and found that TNC services clustered in wealthier neighborhoods, leaving transit deserts underserved. In contrast, Hu and Sun (2023) developed a scenario-based framework showing how subsidized last-mile TNC connections could improve job accessibility for low-income populations in Chicago. Varying subsidy levels and transfer penalties, they found that integration consistently expanded access, though benefits differed across racial, ethnic, and gender groups. Their work shifted attention from ridership metrics to accessibility, highlighting it as a crucial lens for evaluating system-level equity impacts. Finally, Dzisi et al. (2022) reminded scholars that the Global South faces distinct challenges: in Sub-Saharan Africa, where informal paratransit dominates, the issue is not substitution or congestion but formalizing existing systems, placing TNC debates in a broader global context. Together, these works stress the importance of targeting specific groups to improve transit equity and emphasize the role of communication and education in implementing new mobility services. However, despite growing interest, few studies evaluate equity outcomes of actual TNC–transit partnerships, limiting our understanding of who benefits when these programs are implemented in practice rather than theorized.

2.5. Flexible and Semi-Flexible Transit Models

Parallel to research on ride-hailing, scholars have long examined flexible and semi-flexible transit, particularly relevant in low-density areas where fixed routes are inefficient. This literature offers lessons for TNC–transit integration. Quadrifoglio et al. (2006) introduced Mobility Allowance Shuttle Transit (MAST), showing via simulation that flexible routing outperforms fixed routes in low-demand settings and that effectiveness depends

heavily on demand density. Qiu et al. (2015) and Nourbakhsh and Ouyang (2012) extended this work with optimization models that balance coverage and directness, formalizing flexible routing as a structured design problem and Alshalalfah and Shalaby (2012) found in suburban Toronto that service quality in flex-route feeders is highly sensitive to scheduling. However, Berrada and Poulhès (2021) examining economic trade-offs, showed that flexible systems may reduce operating costs but do not always maximize social welfare. Mishra et al. (2020) compared delivery models: route deviation, checkpoint deviation, and demand-responsive replacements, emphasizing the need to balance efficiency and coverage so that neither reliability nor accessibility is compromised. Research in emerging economies further highlighted contextual differences and Ding et al. (2024) demonstrated that optimized flexible pick-up and drop-off zones can reduce deadheading and improve fleet utilization. Sharma et al. (2020) showed that reliability and safety concerns constrain paratransit scalability in India, stressing the need for local adaptation. Collectively, these studies suggest that flexible transit is better suited than fixed routes for low-demand environments. This tendency reinforces the potential role of TNCs as an even more adaptable, on-demand complement to traditional transit which is an area which haven't got enough attention. Despite extensive modeling of flexible transit, very few studies directly compare these systems with TNC-based replacements, leaving a gap in understanding how agency-operated flex services and market-based TNCs perform under similar demand conditions. Very few studies directly compare flexible transit systems with TNC-based replacements, leaving a gap in understanding how agency-operated flex services and market-based TNCs perform under similar demand conditions and the literature still lacks clear guidelines for how agencies should decide between flexible transit and TNC partnerships in low-demand areas.

2.6. Governance Frameworks and Analytical Evaluations

Most studies discussed above examine other flexible modes, such as shuttle services, or treat TNCs as operating alongside but separate from public transit. While some explore interactions between the two, far fewer analyze full integration or coordinated partnerships functioning as a unified system. Existing research on TNC–transit integration increasingly focuses on how governance structures and institutional arrangements influence outcomes. Rather than emphasizing individual pilots, these studies examine integration mechanisms, coordination strategies, and empirical performance to derive broader policy insights. Grahn et al. (2020) and Grahn, Qian, and Hendrickson (2021) evaluated coordinated first/last-mile systems in Pennsylvania through simulations and field data, showing how cost and travel-time efficiencies depend on operational design. The MARTA REACH pilot demonstrated key numeric estimates for redesigning a fixed-route system with on-demand mobility. The on-demand service improved average total travel time for approximately 60% to 64% of all trips compared to the fixed-route alternative. For a sample commuter, the door-to-door on-demand trip averaged 20.86 minutes, which was a significant improvement over the estimated 30 minutes for the fixed route. The estimated cost per rider was high during the pilot, ranging from $36.52 to $51.12, but is projected to drop to a sustainable range of $12.04 to $16.74 if ridership were to triple (Van Hentenryck et al., 2023). Zuniga-Garcia et al. (2020) compared integration strategies in Austin, identifying structural factors such as spatial coverage and demand density that determine when microtransit outperforms TNC-based linkages.

Beyond operational modeling, researchers have studied governance and institutional coordination. Schwieterman and Livingston (2018) and research done by Shared-Use

Mobility Center (SUMC) (2016) synthesized evidence from multiple public–private partnerships, categorizing fare integration, contracted operations, and data-sharing models, while highlighting recurring challenges around accountability, cost recovery, and interagency coordination. International work further demonstrates contextual variability: Miharja et al. (2023), using household travel survey data in Indonesia, analyzed how ride-hailing influenced trip purposes and mode substitution beyond commuting, revealing the broader implications of integration. Scholl et al. (2024) used stated-choice experiments in Latin America to reveal limited willingness to adopt integrated systems even with financial incentives, underscoring cultural and perceptual barriers alongside institutional ones. Frei et al. (2017) validated demand for flexible, demand-adaptive transit in low-demand areas using stated-preference data. They show that waiting time feels less burdensome when riders are picked up at home, Similarly, Nam et al. (2018) demonstrate that integrating shared TNCs effectively solves FMLM gaps, thus expanding transit coverage where fixed routes are impractical. Their simulations confirm that ride-sharing, when well-integrated, increases ridership and improves overall system productivity by strengthening connections to the core network.

2.7. Algorithm for Integrated Mobility and Ride-sharing

Beneath the policy debates and pilot projects lies a core technical challenge: how to design and optimize ride-sharing and integrated mobility systems. Cordeau and Laporte (2007), provided a comprehensive survey of the Dial-a-Ride Problem (DARP), categorizing exact, heuristic, and metaheuristic approaches that continue to serve as a reference point for subsequent algorithmic innovation and flexible service design. Building on this framework, Kumar and Khani (2021) advanced implementation by creating a schedule-based matching

algorithm for ridesharing integrated with transit timetables, while Nickkar et al. (2022) introduced optimization models for temporary stop strategies in feeder services, where their framework successfully balanced user walking distances with operational efficiency, showing that small design decisions can produce large system gains. Other research has further broadened this technical base by addressing dynamic and complex system operation. Nourbakhsh and Ouyang (2012) formalized optimization for semi-flexible transit services, providing structured models for balancing efficiency and coverage in low-demand contexts. This focus on dynamic response was continued by Qiu et al. (2014) who developed dynamic station strategies for flex-route bus operations, demonstrating how flexible routing can be adjusted in real time to respond to variable demand. At the city scale, S. Ma et al. (2015) proposed real-time ride-sharing algorithms coordinating trips dynamically, and Stiglic et al. (2018) simulated the joint design of ridesharing and transit, showing system-level efficiency gains when services are coordinated

Overall, the above works show that algorithmic design is central to making flexible, on-demand mobility systems efficient and scalable, but do not offer frameworks that are easily adaptable for the TNC substitution problem. Yang et al. (2024) provided essential algorithmic insights, which we find relevant to the modeling of on-demand TNC operations. Their development of a Decomposition Heuristic (D-H) enables the scalable management of thousands of shared trips, a capability critical for maximizing vehicle utilization and defining the operational requirements for high productivity in real-time routing. An efficient formulation and solution scheme for modeling TNC services that partially substitute for transit lines was developed along the lines of Yang et al (2024) in this research, as shown in chapter 4.

CHAPTER 3: Stop-level Shared TNC Service with Heuristic Ride Matching

This chapter focuses on using partial substitution of transit operations with TNC operations, aimed at reducing the operating costs of the transit agency while ensuring that service remains accessible to all existing passengers at the current level of service. Within this proposed framework, TNCs provide stop-to-stop service as a substitute for bus operations in segments where ridership is insufficient to justify continued fixed-route service. The bus operation ends at a selected stop, and the bus reverses direction. This is similar to traditional short-turning operations, wherein, typically, some of the bus trips would continue for the whole line length, and only some trips are short-turned. In our case, bus operations along the low-ridership stops are entirely discontinued for the analysis period and substituted by TNC operations.

To implement TNC-substitution, a heuristic is developed that matches passengers for shared TNC-rides between stops, for least-cost TNC operations. An important component of the framework is the selection of an appropriate service-truncation point for the bus line, which must account not only for the physical and operational feasibility of potential stops but also for the productivity of the bus service beyond the truncation location. Because bus productivity is largely determined by the number of passengers on board or expected to board or alight after truncation, careful evaluation is required to ensure that resources are reallocated in a way that improves efficiency without compromising accessibility. This study utilizes empirical data from Long Beach Transit to demonstrate the step-by-step application of the methodology and to present the resulting numerical analysis.

3.1. Route Analysis Approach

Figure 3-1 presents a map of Long Beach, CA Transit with all bus stops, on which the stops for Route 93, as an example, are highlighted in green. The downtown area is indicated by a circle. Prior research (Murphy et al., 2022) has shown that bus ridership is significantly lower in areas located farther from the city center. As the focus of this study is on low-demand outlying segments, we concentrate on the route ends away from downtown.

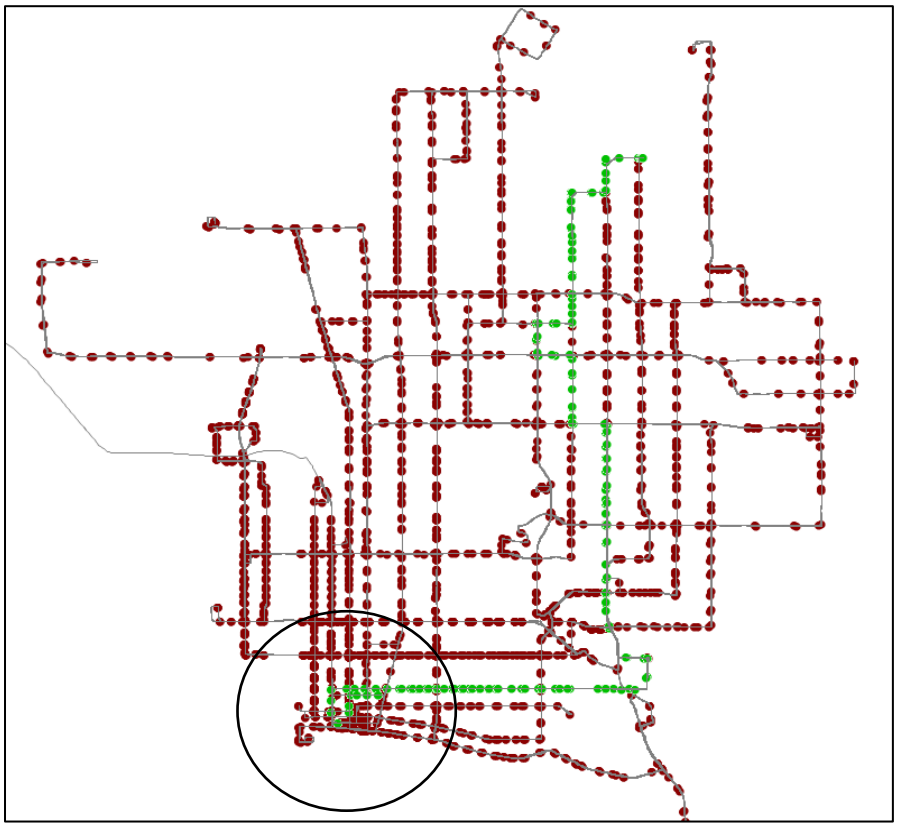


Figure 3-1 : Long Beach Bus network with route 93 (green-dots stops) and downtown area (circle)

Similar to Long Beach, in many U.S. cities, transit systems were planned to concentrate service in dense urban cores where ridership potential is highest and extend outward to suburban or peripheral areas with lower demand. As a result, the spatial layout

of routes often mirrors the same demand gradients. Similarly, another example of Tulsa, OK, illustrated in Figure 3-2, shows multiple bus routes converging in the downtown area and terminating in low-density suburban zones. The prevalence of such low-demand terminal segments is a common feature across urban networks. Although the algorithms proposed in this dissertation are not limited to the end segments of bus routes, these recurring cases are used as representative examples and serve as the main focus of the study, providing a relevant context for addressing efficiency challenges in transit service design and operation.

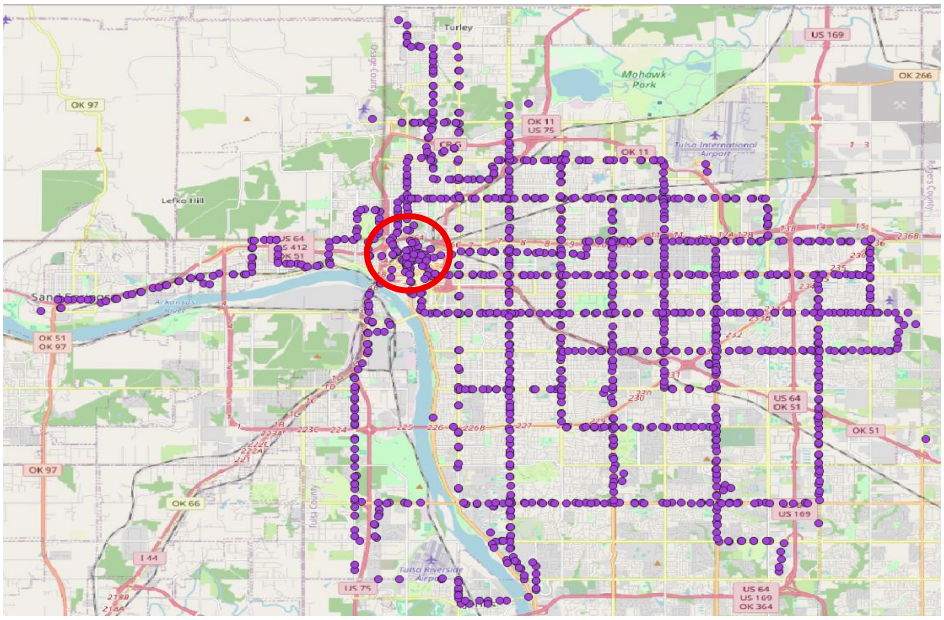


Figure 3-2 : Tulsa, Ok, Bus network with downtown specified

To address this issue of reducing ridership on segments away from the downtown area, truncation of the first and/or final few stops of the route is considered. In this context, truncation refers to the elimination of certain stops at the beginning or end of a route during specified periods. Specifically, inbound trips that begin in the suburbs and terminate in the downtown area are analyzed for potential elimination of initial stops, while outbound trips that originate downtown and extend into the suburbs are examined for possible removal of

terminal stops. Under the proposed scheme, passengers whose trips involve these truncated stops would be served by TNC vehicles, thereby preserving access. Importantly, a single fare payment, equal to the standard bus fare, is assumed for the entire trip, as the proposed operation is designed to maintain the same service level and cost for passengers. The passengers request ride through transit or TNC app or call center beforehand. If both the origin and destination of a passenger are located within the eliminated stops, the passenger is served entirely by a TNC vehicle. If both locations fall within the active bus stops, the passenger receives a regular bus ride. For trips where one location is an active bus stop and the other is an eliminated stop, the passenger is served by a combination of bus and TNC service. Specifically, if the bus line is truncated after the passenger's boarding stop, a TNC vehicle provides the initial pickup, transports the passenger to the truncation stop, and the journey continues by bus. Conversely, if the passenger's alighting stop lies within the eliminated portion of the line, the bus carries the passenger from their origin stop to the truncation stop, where they transfer to a TNC vehicle for the final leg of the trip.

Table 3-1 summarizes these service patterns, and Figure 3-3 illustrates them schematically. The figure presents two panels: the first depicts passenger movements 1 through 5, and the second depicts movements 6 through 10. Each dot represents a transit rider who has requested a trip in advance, while arrows indicate the corresponding movements of buses and TNC vehicles. These operations may occur: (a) simultaneously, (b) in coordination with segment travel times to ensure that TNCs and buses arrive at the truncation stop concurrently, minimizing transfer times for passengers, or (c) with slight delays that may require passengers to wait briefly at the truncation stop.

Table 3-1 : Summary of sequences of bus and TNCs movements

Sequence	BUS	TNC
1	A bus carrying passengers proceeds toward the low-demand portion of its route.	A TNC vehicle enters service from the opposite end of the truncated segment to pick up the first passenger request.
2	The bus continues along its active stops, where passengers may board or alight as usual.	The TNC vehicle travels toward the downtown area, bypassing inactive stops if no pickup or drop-off requests exist.
3	The bus arrives at the designated truncation stop, now serving as its final stop.	The TNC vehicle may pick up additional passengers along the way if requests exist and capacity is available.
4	All passengers remaining on the bus alight at the truncation stop.	The TNC vehicle arrives at the truncation stop.
5	The bus performs a loop or U-turn in order to begin its return trip toward downtown.	Passengers alight from the TNC vehicle and wait at the truncation stop.
6	Passengers from the TNC vehicle board the bus at the truncation stop.	The TNC vehicle may either (a) turn back to provide service in the opposite direction, (b) exit service, or (c) be reassigned to another route with active truncation operations, depending on contractual arrangements.
7	The bus resumes its route toward downtown, stopping at subsequent active stops.	Passengers alighting from the bus who need to continue to inactive stops board an available TNC vehicle. If demand exceeds capacity, additional vehicles are dispatched.
8/ 8’	Passengers board the bus at subsequent active stops as in normal operations.	TNC vehicles serve inactive stops, stopping only when pickup or drop-off requests are present.
9/ 9’	The bus continues along the remainder of its route toward downtown.	TNC vehicles may stop along their path to fulfill requests, provided seating capacity is available.
10	____	TNC vehicles continue serving all inactive stops until all passengers are dropped off, after which they may either turn back, exit service, or be reassigned as needed.

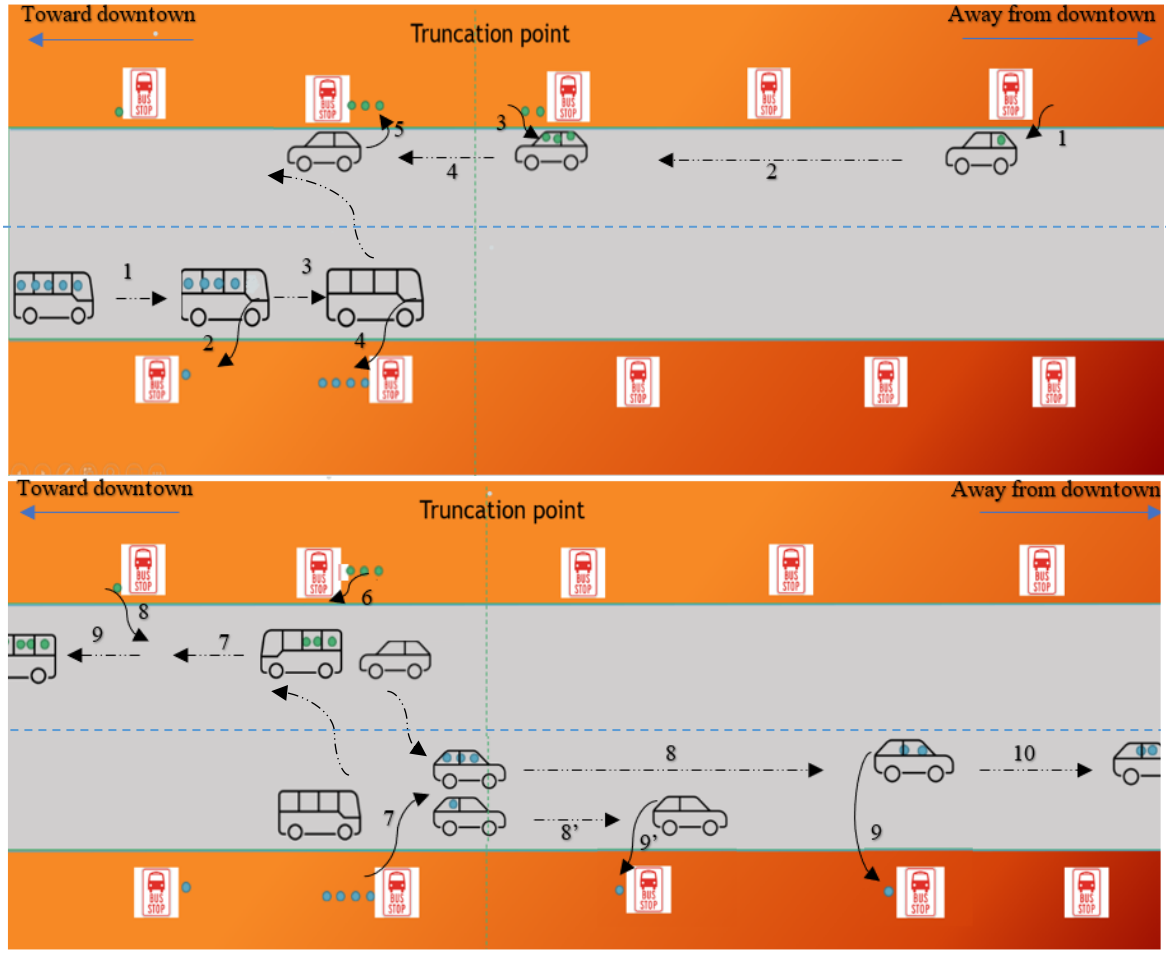


Figure 3-3 : Bus and TNCs' operation before and after the truncation point

3.2. Selecting Candidate Routes/Segments for Truncation

A ranking system is proposed to identify candidate routes prior to applying the truncating and TNC substitution algorithm. For this purpose, a bus is considered less productive when the number of passengers carried is substantially below vehicle capacity along any segment between stops. The minimum passenger threshold used to determine what is 'productive' is agency-dependent and can be determined after system-wide cost estimation, as it may vary according to factors such as vehicle type, fuel costs, and driver wages. For the purposes of this study, three thresholds were examined as cutoff criteria: 4,

6, and 10 passengers. Segments at the beginning or end of routes, particularly those away from the downtown area, where bus ridership falls below the criterion, are identified as candidates for truncation.

Inbound trips were analyzed by examining passenger loads starting from the first stop. All consecutive stops and segments with ridership below the criterion were selected for truncation until reaching the first segment that exceeded the threshold. Given the number of passengers on board as well as the distances and travel times between stops, passenger-miles and passenger travel times were calculated to determine the service requirements if these trips were instead served by TNCs. The aggregate distances and times for the truncated segments (without weighting by passenger counts) were then used to estimate the potential savings in bus VMT, VHT, and operating costs resulting from truncation. Outbound trips were analyzed similarly, except that the truncation points were determined at the end of routes, beginning with the last stop and moving backward until a segment exceeded the ridership threshold.

After identifying truncation points for every bus line under consideration, applied in this case to the entire set of LBT (Long Beach Transit) routes for early morning trips, the ridership numbers on the segments with TNC-substitution were tabulated across all bus routes to estimate route-level performance. Using VMT, VHT, and ridership information, the cost implications of truncation were then assessed. This preliminary estimation, however, requires assumptions regarding the efficiency of passenger pooling in TNC operations, which are addressed in the following section. These assumptions are necessary only for the initial screening of routes to identify candidates for truncation, after which the study advances to a more detailed evaluation scheme designed to minimize costs through optimized TNC

substitution. Equations (3-1) to (3-5) show the assumption and methods for the estimation of costs for initial route assessment. The TNC cost represents the total payment made by the transit agency to the TNC, under the assumption that passengers pay only the standard transit fare. Accordingly, this cost is intended to cover driver compensation from the TNC, the company's share that includes their expenses and profit. These cost estimates were obtained by a limited field study of querying the TNC application during off-peak hours in the study area for trips of varying lengths and locations.

TNCs' cost assumptions for route selection:

$$n_t = n_p / \alpha \quad (3\text{-}1)$$

n_t : Number of needed TNCs per bus trip

n_p : Total number of passengers to be picked up before the truncation stop in trips

α : Average number of people in any TNC car at the pick-up stop (assumption α = 2)

$$VMT = m_p/1.5 \quad (3\text{-}2)$$

We assume that 1.5 people can carpool in TNC vehicles considering the mileage they are carpooling.

VMT : TNCs' total mileage

m_p : *Passenger total mileage*

$$c_{TNC} = c_v \times n_t + c_{mv} \times VMT \quad (3\text{-}3)$$

c_{TNC} : Total TNC cost

c_v: Cost per vehicle (assumption c_v = $3 per vehicle)

c_{mv}: Cost of TNCs per mile (assumption c_{mv}= $2 per mile)

Bus cost assumptions (First for selection of route and then to compare truncation points):

$$c_{bus} = c_{bt} \times t_b + c_{mb} \times m_b \quad (3\text{-}4)$$

c_{bus} : Total saved cost from not operating buses

t_b: Bus saved hours

m_b: Bus saved mileage

c_{bt}: Bus cost per hour (assumption according to LBT: c_{bt} = $54.75 per hour)

c_{mb}: Bus cost per mileage (assumption according to LBT: c_{mb} = $ 2 per mile)

$$b_{total} = c_{bus} - c_{TNC} \quad (3\text{-}5)$$

b_{total} : Total saving

Note that the bus cost per hour used here (roughly around $100 per hour, considering about 25 miles of bus travel) is somewhat less than what is found in public transit systems in the US (typically near $150). LBT who funded this study prescribed the above figures.

Using the above formulas, total savings were calculated for all routes at different truncation criteria, and a prioritization table was developed to identify and rank the routes that provide the greatest overall savings and overall net savings. This is shown in Table 3-2 in section 3.5 on numerical results that follows the description of the costs of TNC operations in the next two sections.

3.3. TNC Substitution Algorithm

Using the route identifying scheme developed in the previous section, the routes with the greatest potential savings can be identified as study routes for truncation. Based on the bus network map, potential truncation points are suggested as candidates (options), taking

into account both productivity and physical feasibility. A suitable truncation location is typically near an intersection, where a bus can perform a loop or U-turn to begin its return trip. Accordingly, the analysis focuses on stops located near intersections in areas farther from the downtown core. The selected cut-off points should not be placed too far from each other along either the inbound or outbound direction, in order to avoid requiring buses to travel out of service for multiple segments.

For outbound trips terminating at a truncation stop, passengers alight from the bus and transfer to TNC vehicles. The required number of TNCs is estimated based on passenger load, assuming each vehicle has a capacity of three passengers. This assumed capacity can be different based on the agencies' or TNCs' policies. If demand to later stops exceeds the available capacity, additional TNC vehicles are dispatched as needed. We assume that there is no limit on the availability of TNC vehicles.

For outbound trips from the city center or higher-ridership area, the passengers are grouped into vehicles according to their remaining travel distance, with those traveling farther assigned together. This way a vehicle might have a smaller number of passengers with them having nearest destinations This grouping allows vehicles that serve shorter trips to complete their service earlier and subsequently be redeployed for other trips or in the opposite direction. As passengers are dropped off during a TNC trip, their vacated seats become available for new requests at subsequent stops. For inbound trips, TNC vehicles are dispatched incrementally, starting with a single vehicle at the first request stop. Passengers board sequentially, and when the three-passenger capacity is exceeded, a new vehicle is introduced. If passengers alight before reaching the truncation stop, their seats are immediately freed for subsequent requests. This approach allows for precise estimation of

the number of vehicles required at each stop and time. Upon arrival at the truncation stop, all TNC passengers transfer to the bus to continue their trips.

TNC vehicles stop only when there is a pickup request with available seating or when dropping off an onboard passenger. The sequence of these pickups and drop-offs defines the service path for each TNC vehicle. Once the full set of vehicle paths, stops, and timings is determined, VMT and VHT are computed. The associated costs of TNC operations are then calculated using equation (3-3).

An important consideration at this stage is determining how passengers should be assigned to TNC vehicles. The grouping of passengers within vehicles can be optimized to improve overall system efficiency. Equation (3-6) introduces a simplified cost function designed for this purpose, providing a basis for optimizing passenger allocation and minimizing total operational costs.

$$C = \delta \times n + \gamma \times VMT + \theta \times s \qquad (3\text{-}6)$$

C = *Total cost*

n = *Number of TNC vehicles*

VMT = *Vehicle Miles Traveled (total TNC vehicle mileage)*

s = *Total number of stops experienced by riders during their trips*

Decision variable here is n which is the number of vehicles. The coefficients δ, γ, and θ are weighting parameters that reflect the relative importance of the corresponding variables in the cost function. Based on the cost of calling and operating a TNC vehicle, the following assumptions are made: δ = \$3.00, representing the minimum cost of dispatching a TNC vehicle; and γ = \$2.00 per mile, representing the operating cost per unit distance. The coefficient θ, which captures the effective disutility experienced by passengers due to additional stops made by a TNC vehicle, is more difficult to estimate in the absence of user-

response data. For the purposes of this study, θ is set to zero, but its inclusion in the model highlights the importance of considering passenger disutility in practical applications. In real-world deployments, pilot studies of TNC operations and passenger responses would be needed to empirically estimate θ, or alternatively, adaptive learning algorithms could be employed to iteratively update the parameter values over time.

An optimization of TNC passenger-pooling operations can, in principle, be formulated using this cost function as the objective. Such a formulation corresponds to a pick-up and delivery problem. However, in this chapter, a simpler approach is preferred. It is worth noting that the linear nature of the transit line problem, where TNC vehicles operate only along the streets of the bus line, offers a more tractable structure for optimization. A sequential (greedy) heuristic can be applied to approximate pooling decisions, provided that the disutility of intermediate stops for additional passenger pickups is disregarded. In this heuristic, passengers are sorted by distance to their destinations and given a ranking, and grouping decisions are made accordingly. The assumptions underlying this grouping strategy are as follows:

- When multiple vehicles are in operation, passengers with longer remaining travel distances are grouped together.
- Vehicles may stop solely for the purpose of exchanging passengers, even without a pickup or drop-off. This can happen especially when a new pickup is requested with a passenger who has farther destination compare to the passengers in a full TNC vehicle (similar to the example that is shown in Figure 3-4),
- Grouping passengers and evaluating their ranking (distance to destination) are updated dynamically at each stop.

Figure 3-4 provides an illustrative example of this ranking algorithm and reports the corresponding objective function value.

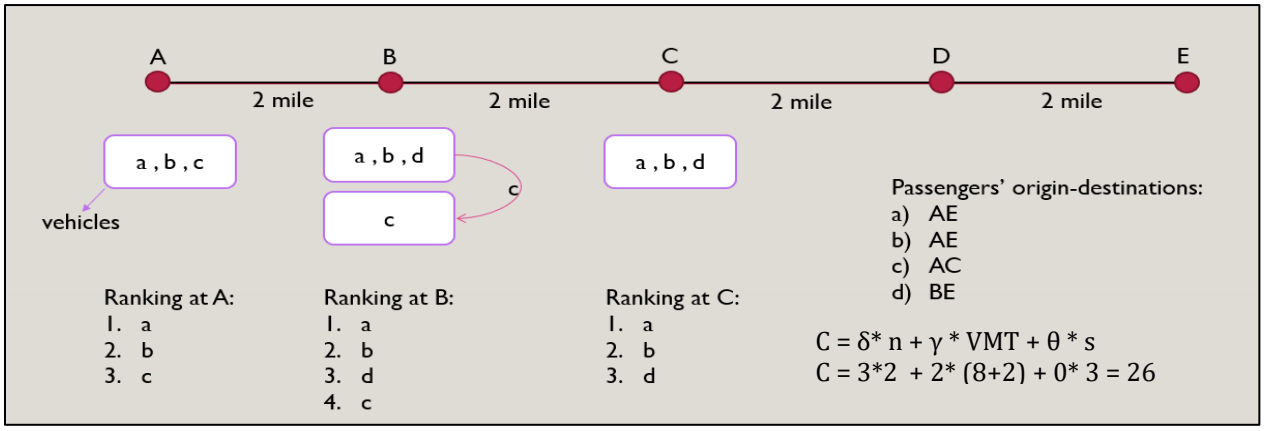


Figure 3-4: Example of TNC Passengers grouping by ranking heuristic

We define a TNC vehicle trip as the sequence of movements, pickups, and drop-offs performed by a vehicle while continuously carrying a passenger, such that the vehicle is never empty. After passengers are grouped and all of these trips are formed, chains of trips are generated to minimize the total number of TNCs required. To achieve this, a heuristic algorithm was developed with the objective of maximizing the number of trips assigned to each vehicle while minimizing total travel time. Empty mileage and idle time can be included in the cost calculations, as they represent an important factor for the transit agency when designing contractual agreements with TNCs. It is important to note, however, that alternative algorithms for grouping trips and constructing vehicle chains could also be applied, depending on the cost metrics, optimization objectives, and preferences of the transit agency or the TNC operator.

The methodology also accounts for delays. A value of two minutes is included in the VHT calculation for each pickup, drop-off, or transfer at truncation stops or inactive stops. These dwell times are comparable to those of buses, meaning the primary additional delay

arises from transfers between buses and TNCs. However, since TNCs serve fewer stops, passengers may experience shorter travel times on inactive segments compared to bus operations. As the transfer from/to transit vehicles happen according to posted line schedule, the passenger pick-up and drop-off time windows are known. The transfers can then be scheduled without significant waiting time, and transfer delays and disutilities can be minimal. The trade-off between the convenience of TNC vehicles (with potentially faster travel times) and the inconvenience of transfers should ideally be quantified through traveler behavioral surveys conducted in pilot projects. The results of such studies could then be incorporated into the proposed algorithms to further refine system design and improve passenger experience.

3.4. Contractual Structures

Total TNC costs, grouping passengers, and chaining trips depend a lot on the rates negotiated between the agency and the TNC. For example, a high rate per mileage compared to per vehicle, might encourage transit agencies to request many vehicles instead of forming a trip chain for several passengers so that they can avoid having empty mileage in between. The following subsections describe three basic types of structures that are conceivable. This is certainly not an exhaustive list of partnership possibilities

1. Full-hire contract: All required TNC vehicles are hired from the time the first vehicle is needed until the last vehicle completes its service. In this case, vehicles are reused across different trips, but because the full fleet remains available throughout the period, some vehicles may complete fewer trips in their chains. This approach is costly, as some vehicles and drivers may remain idle for significant portions of the contracted period. However, this idle time provides additional flexibility, accommodating late app or call requests.

2. Trip-chain contract: Each vehicle is hired only for the duration of its active trip chain. Some vehicles may be active for only a few minutes, serving as few as two stops, while others may operate for longer chains. Vehicles assigned to trip chains are compensated not only for passenger-carrying mileage but also for empty mileage and time between trips. This arrangement, that has lower overall cost, reduces idle time and offers less flexibility than the full-hire contract. It is still allowing for limited accommodation of late app request if the passengers can be picked up and delivered on the path that TNC vehicles were going to relocate empty between trips.

3. Per-trip contract: In this structure, vehicles are compensated solely for individual TNC trips, and no vehicle chains are formed. While passengers are still grouped into trips to improve efficiency, each trip is considered independently, requiring a new vehicle call. This approach entirely avoids payment for empty VMT. and costs least among these cost structures.

Here we made a simplifying assumption that the rate of per mileage or per request is the same for all contract types which is not accurate in practice. The costs of these contracts are estimated based on VMT and the number of vehicle calls. In practice, the most cost-effective contract type will depend on specific truncation structures, operational priorities, and negotiation outcomes. Different contract types may also necessitate different algorithms for grouping trips into chains. Ultimately, the public transit agency plays a central role in guaranteeing bus-like service to passengers at the same fare level as the fixed-route bus system. Since fare revenues remain unchanged, optimizing TNC operations under appropriate contractual frameworks is critical to minimizing expenses and ensuring the financial viability of TNC substitution. The following section applies these contract

structures and methodological assumptions to the Long Beach Transit case study, presenting the numerical results of the proposed framework.

3.5. Numerical Result:

Long Beach Transit Data Sources:

An Automated Passenger Counter (APC) device is used in LBT that automatically counts passengers when they board or alight the bus and then generates stop-level, trip-level, and route-level APC data. APC data provides averaged boarding and alighting counts for each stop, each trip, each type of day (weekday and weekend), which are used by this study. When analyzing bus trips, LBT filters the bus trips based on the time of the bus departure from the first stop of the route and then they put trips in 6 groups (periods of the day), namely, Early Morning (before 6:00 AM), AM Peak (6:00 - 8:59 AM), Midday (9:00 AM - 2:29 PM), PM Peak (2:30 - 5:59 PM), Evening (6:00 - 8:59 PM) and Late night (after 9:00 PM).

Scheduling data is exported from thetrip scheduling software, HASTUS (Giro Inc., 2025) used by LBT, in a series of General Transit Feed Specification (GTFS) files. These files are in a standardized format for all transit agencies and are shared publicly with developers for use in trip planning applications. The text files contain information such as route shapes, stop locations, and stop arrival times for all trips in a service change period. For the purpose of this study, the GTFS files were appended to the road network layer, and a transit network layer was created, which contains useful information such as the number of trips per segment and by time period. Then APC data was added to the transit network layer. The result is a dataset that contains trip and ridership information by segment, which was used for this analysis.

Boarding and Alighting Numbers:

In the dataset prepared in the previous paragraph, passenger boarding and alighting numbers are reported as average values. For the purposes of this analysis, these values are rounded up to the nearest integer to avoid fractional counts. This rounding approach provides a conservative estimate, ensuring that the required number of vehicles and associated costs are calculated closer to a worst-case scenario. The rounded values are then used to compute the number of passengers on board for each segment of the bus route. After each stop, the passenger load is updated according to the following formulation:

$$n(i) = n(i-1) + b(i) - a(i) \qquad (3\text{-}7)$$

where,

$n(i) =$ *Number of passengers after stop i*

$b(i) =$ *Number of passengers boarding at stop i*

$a(i) =$ *Number of passengers alighting at stop i*

The calculations are conducted under the following assumptions. First, buses are assumed to begin each trip with zero passengers prior to the first stop. Second, all remaining passengers are assumed to alight at the final stop of each bus trip. Finally, if the computed number of passengers on board results in a negative value due to the use of rounded averages, the passenger load is set to zero.

Using the method described in Section 3.3, estimates of the total savings from truncation and bus substitution were calculated for each route under different cutoff criteria. These results were then organized into a table in descending order of savings. Table 3-2 lists the top Long Beach Transit routes during the early morning period with the highest savings for cutoff criteria of 4, 6, and 10 passengers. This table also shows the number of passengers

who will need to use TNCs instead of buses as a result of this truncation. The results indicate that total benefits are generally greater when the cutoff criterion is set at 4 passengers compared to higher thresholds. Routes 91, 92, and 93 consistently rank among the best candidates, particularly for the 4- and 6-passenger cutoffs. Notably, (Murphy et al., 2022) had previously identified these same routes as suitable for improvement, based solely on their low ridership patterns. This chapter presents the scenarios and results for Route 93 during the early morning period as a representative example.

The algorithm also identifies the specific stops in each trip where bus loads fall below the chosen ridership threshold. For a given route, these potential truncation points may differ across bus trips and between inbound and outbound directions. When truncation points for multiple trips (during the analysis time period) are located near each other, an intermediate stop can serve as an effective common truncation point for applying the TNC substitution scheme. However, when potential points are more widely separated, multiple alternatives may need to be tested to determine the optimal location. Figure 3-5 illustrates route 91 as an example, with stops before/after which the bus ridership is below the criteria of 4 people for different inbound and outbound trips in the early AM, respectively.

Table 3-2: LBT routes saving after truncation and substitution in early AM

10 passenger cut-off			6 passenger cut-off			4 passenger cut-off		
Routes	**Saved cost per day**	**# Shifted riders**	**Routes**	**Saved cost per day**	**# Shifted riders**	**Routes**	**Saved cost per day**	**# Shifted riders**
91	$90.97	23	91	$92.60	16	172	$95.39	8
92	$62.90	13	172	$82.17	19	91	$84.81	13
172	$54.16	34	92	$80.37	5	92	$80.37	5
45	$22.15	25	93	$60.75	32	93	$66.16	28
171	$21.35	30	171	$50.83	19	171	$60.24	9

10 passenger cut-off			6 passenger cut-off			4 passenger cut-off		
Routes	**Saved cost per day**	**# Shifted riders**	**Routes**	**Saved cost per day**	**# Shifted riders**	**Routes**	**Saved cost per day**	**# Shifted riders**
21	$20.37	5	121	$25.49	4	121	$32.88	3
22	$16.61	33	22	$27.43	18	192	$32.57	16
121	$5.16	15	45	$24.46	15	46	$31.48	16
94	$0.68	9	21	$20.37	5	22	$31.38	14
46	$0.43	36	46	$19.40	24	191	$24.33	28
151	$4.95	14	23	$8.09	1	45	$23.56	11
23	$-15.09	12	94	$7.51	5	21	$20.37	5
93	$-17.95	44	173	$5.63	24	173	$17.45	10

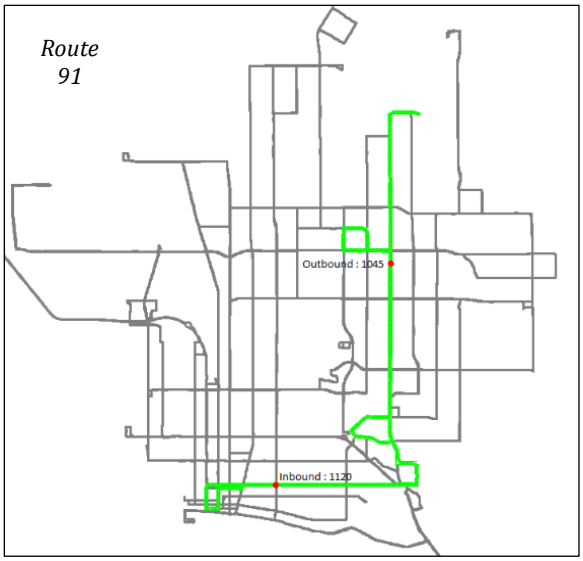


Figure 3-5: Route 91Stops where the criteria are met

3.6. Candidate Selection

In this study, 'candidates' refer to potential truncation points identified on the basis of both physical feasibility and ridership data, as described above. These candidate points are located at stops near intersections where buses can conveniently reverse direction to begin their return trips. For each candidate, all stops located beyond that point, outbound or

inbound depending on trip direction, are treated as inactive during the period of truncated service. Figure 3-6 illustrates the set of candidates considered for Route 93 during the early morning period. Practical considerations play a critical role in this process. For example, candidates 3 and 5 were reviewed and approved by LBT specialists as feasible truncation points, since they are located near shopping malls with large parking lots that provide sufficient space for bus turnaround operations.

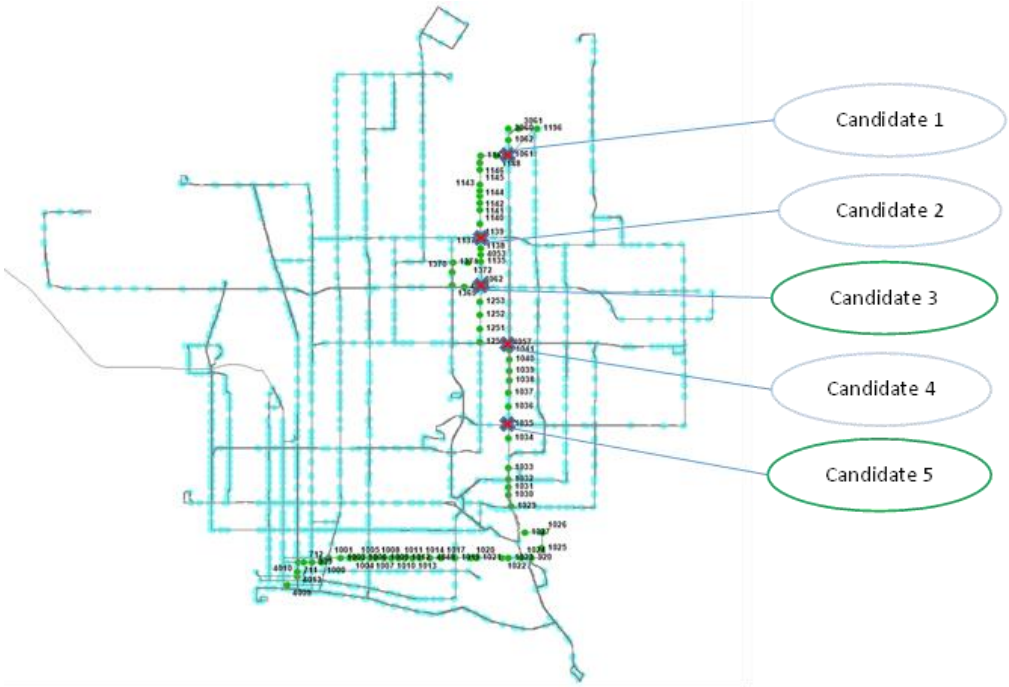
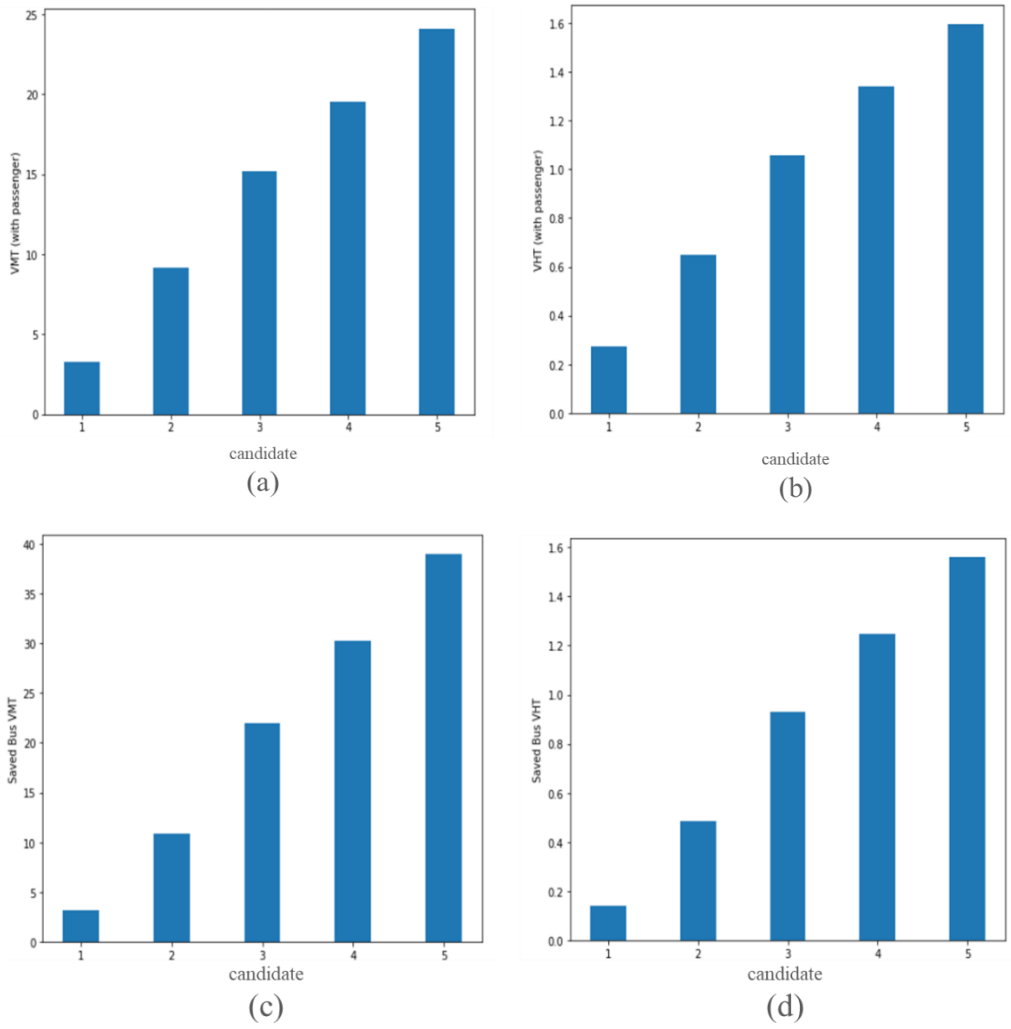


Figure 3-6: Route 93 Stops and suggested Candidates in Early Morning

For each candidate truncation point, all early-morning bus trips in both directions were analyzed. The required number of TNC vehicles was determined by allocating passengers to available seats, after which the associated costs were estimated using Equations (3-3) and (3-4). These estimates were then compared across candidates. To evaluate total savings, different contractual structures were applied in order to provide an

overview of the potential outcomes under each arrangement. The results of this analysis are presented in Figure 3-7 and Figure 3-8 , which illustrate the performance of the algorithm for the selected candidates.



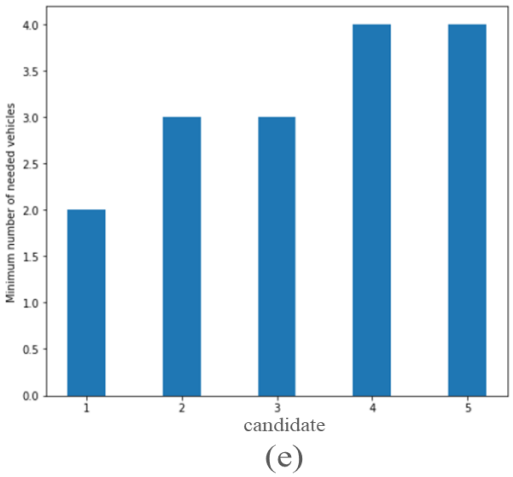


Figure 3-7: (a) VMT and (b) VHT of TNCs (with passenger) Total saved buses' (c) VMT and (d) VHT, (e) Minimum number of needed TNC vehicles

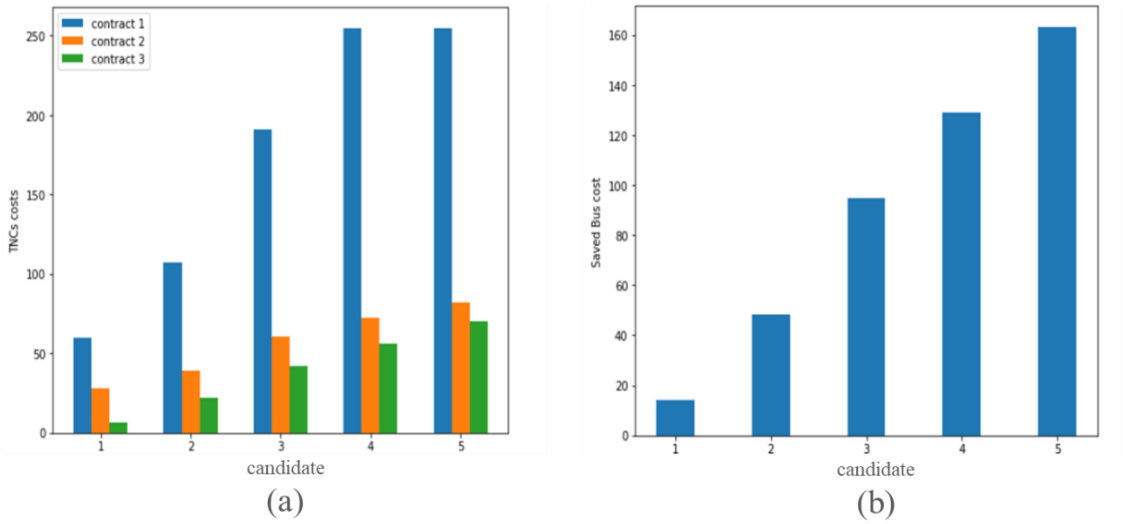


Figure 3-8: (a) Estimated cost for the suggested contract types, (b) Saved cost of not using the buses for the TNC-substituted segments

A comparison of total benefits, defined as the savings from reduced bus operations minus the costs of TNC substitution, shows that for route 93, contract 3 consistently yields the lowest cost, while contract 1 is generally not beneficial. Candidates 3, 4, and 5 are cost-effective under contract Types 2 and 3, with candidate 5 producing the greatest net savings. In fact, further analysis indicates that implementing truncation at the location in candidate

5 could reduce VMT and VHT sufficiently to eliminate the need for one whole bus trip in the early morning period.

A key question concerns how calculated operational savings translate into actual monetary savings. For example, if a bus and its driver remain idle at the truncation point until the scheduled return trip, then only fuel-related VMT savings are realized, which represent only a fraction of total costs. In the example above, manual inspection showed that candidate 5 allows one outbound bus to serve the truncation point and return, instead of requiring two buses operating from both ends of the line. However, in most urban contexts, such straightforward bus and driver resource savings may not occur. Realizing actual monetary benefits requires reconfiguring schedules at the network level and reallocating saved buses and drivers to higher-demand segments, where they can increase service frequency and productivity. This process typically requires detailed scheduling analysis supported by specialized software and is beyond the scope of this study.

Bus routes' truncation and substitution with TNC service offer several benefits:

- Maintaining equitable accessibility by ensuring that all current users continue to receive service.
- Preserving existing ridership while reducing overall operating costs.
- Potentially reducing passenger travel times, provided that bus schedules are adjusted and the two systems are synchronized.
- Decreasing travel times and the number of stops for TNC vehicles, if pooling operations are optimized.

3.7. Summary of Heuristic TNC Ride-matching

This chapter established a methodology for estimating costs using bus-capacity-based criteria to identify the least productive bus segments. While the framework is broadly applicable to any city, route, or time period, the analysis here focused on early-morning service on Long Beach Transit routes. For several routes, specific stops were identified as potential truncation points, beyond which TNC substitution could be tested as a cost-saving strategy. The findings demonstrate that TNC operations can be beneficial when unproductive segments are carefully identified and when efficient passenger-pooling and contracting schemes are implemented. The analysis also highlights the importance of contract design, as different contract structures influence trip chaining, pooling strategies, and ultimately the choice of truncation points.

This chapter does not fully account for passenger experience, particularly the potential disutility that riders may perceive when transferring between TNCs. Such disutility can directly influence perceived service quality and overall system performance, yet it is not explicitly modeled here. Furthermore, the ride-matching algorithm applied to TNC operations is deliberately simplified, relying on a heuristic approach that, while computationally efficient, does not capture the complexity of real-world ride-pooling dynamics. The cost structures and pricing assumptions are likewise limited, as only a small set of contract types and payment schemes are considered. These assumptions may not reflect the diversity of arrangements negotiated between transit agencies and TNCs in practice, where factors such as surge pricing, driver incentives, and minimum revenue guarantees can substantially alter outcomes.

Despite these limitations, the methodology developed in this chapter serves as a valuable first step. Its simplicity allows for rapid assessment of network compatibility with proposed service changes, offering agencies a practical screening tool to identify promising candidate routes and truncation points. However, the limitations also highlight the need for a more detailed and robust framework. To address these shortcomings, Chapter 4 introduces an advanced methodology that explicitly incorporates passenger disutility into service evaluation, applies a rigorous optimization model for TNC ride-matching, and considers a wider range of contract structures and pricing mechanisms. In doing so, Chapter 4 extends the analysis beyond preliminary screening, providing a more realistic and comprehensive assessment of the feasibility and impacts of transit–TNC substitution. Thus, the transition from Chapter 3 to Chapter 4 reflects a progression from preliminary evaluation to detailed optimization and policy relevance.

CHAPTER 4: Door-level Shared TNC Service with PDPTW Solution

Building on the preliminary screening framework developed in Chapter 3 for TNCs operating from bus stops, this chapter considers a service area around transit stops with TNC operations to/from the actual origins and destinations of the passengers. While we call this "door-level" service, it is not a common terminology. We do not imply service to actual doors, as in the case of paratransit operations with door-level wheel chair access. The TNC service we consider is to/from a curb point near the door at the passenger origin or destination location. Such TNC services can increase ridership by eliminating the walking disutility for travelers. However, owing to the lack of related behavioral data in our case study context, the research here assumes inelastic travel demand, which in turn implies that the estimated benefits from TNC substitution are conservative.

The chapter also advances the analysis by introducing a detailed optimization-based methodology for evaluating transit–TNC substitution. Whereas Chapter 3 identified low-productivity fixed-route segments and estimated potential cost savings using simplified assumptions, the present chapter incorporates additional real-world complexities that are essential for determining whether substitution is operationally and financially viable. In particular, this chapter explicitly models passenger disutility associated with transferring between buses and TNC services, introduces a rigorous ride-matching optimization to determine vehicle assignment and pooling, and evaluates a broader range of TNC compensation structures. These enhancements address the key limitations identified previously and enable a more comprehensive and realistic comparative assessment.

The objective of this chapter is to develop a decision-support model that integrates fixed-route transit operations with on-demand TNC services under multiple operational and

contractual scenarios. The model generates a synthesized set of passengers based on transit agency boarding/alighting data at the stops, assigns certain locations in the TNC service areas near the stops as their Origin and/or Destination point. The framework then proceeds to simulate how the passengers move through the system, how buses and TNC vehicles facilitate passenger transfer at truncation points, how the TNC vehicles are dispatched/routed, and how different contract types influence total system cost and passenger experience.

A key element of the framework is the incorporation of a pickup and delivery optimization formulation that we develop to model the associated TNC vehicle routing. The optimization model works over a set of demand points in the service area, and replaces the heuristic vehicle dispatch model in chapter 3, which is applicable only for stop-level TNC dispatching, not door-level in the service area.

Unlike the initial screening framework in Chapter 3, which emphasized feasibility, this chapter quantifies performance trade-offs, allowing agencies to evaluate service quality impacts and financial implications simultaneously. By doing so, Chapter 4 refines the substitution concept from an exploratory idea to an analytically grounded operational strategy. From a planning perspective, the transit agency considers the option of introducing TNC services to replace some segments of selected fixed-route buses in low-demand areas and/or off-peak hours. After the substitution, normal fixed-route service ceases at certain bus stops, where passengers transfer to TNC vehicles. We name these bus stops as truncation points. Truncation points usually appear as a pair of bus stops on both sides of the road. Before running the new integrated service, bus schedule shifts and truncation point locations are well-broadcast to passengers in advance. We present an example in Figure 4-1 to

demonstrate operational details of buses and TNC vehicles after the fixed-route service ceases at truncation points.

In outbound bus trips (which are to the right direction in the Figure 4-1 example), when a fixed route bus reaches the low-demand segment of its route, it stops at the designated truncation point, where all passengers, who were initially supposed to continue their journey on this bus, leave the bus. TNC vehicles C and D provide ride-sharing trips to all the passengers and drop them off at their destination locations (C1, C2, C3, and D1), which are situated along the truncated segments of the route. In the reverse direction (inbound trips), passengers at location A1 and A2 are picked up by TNC vehicle A, and passengers at location B1, B2, and B3 are picked up by TNC vehicle B. Both vehicles then proceed to the truncation point, labeled as location A3/B4. Schedule coordination enables passengers to be dropped off before the fixed-route bus leaves the stop. For passengers whose origins and destinations are both within the truncated segments, regardless of their travel direction, TNC vehicles provide a direct shared ride between their origins and destinations.

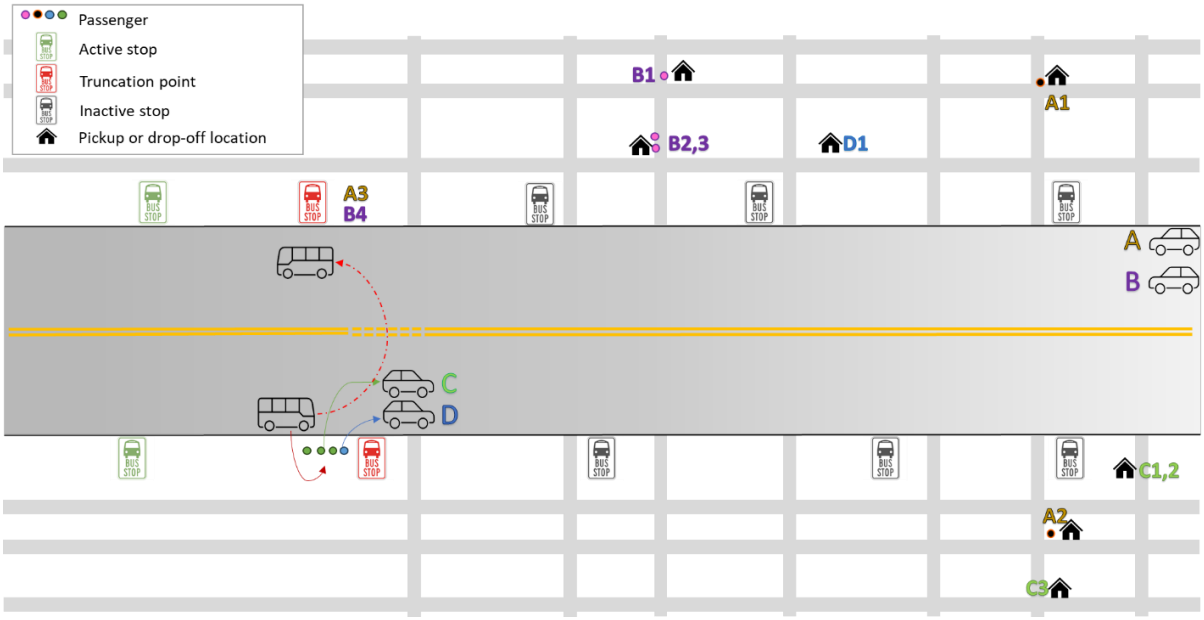


Figure 4-1: Operation of buses and TNCs after the truncation points

The decision problem for transit agencies is whether to replace a certain segment of fixed-route transit with TNC service. A viable substitution scheme should consider the following criteria that apply to the three main stakeholders who would be affected by the service shift:

- For the transit agency, a reasonable cost of hiring TNCs to provide the service needs to be considered. One alternative is to require the TNC cost to be not higher than the cost of running normal fixed route buses to maintain financial sustainability.
- For transit riders, the level of service should not be lower than that of a normal untruncated bus service. That is, their travel schedule should not be delayed. For example, a passenger who originally caught the first bus should not be delayed for the second one. This criterion is guaranteed in the step of estimating passenger ODs and travel schedules.
- For TNC drivers, the hourly compensation should be no less than the average expected hourly minimum income.

The passengers pay only the standard bus fare, and the TNC cost is what is paid by the transit agency to the TNC. This cost should cover driver compensation by the TNC, company expenses, and any associated profit. In this chapter, we first estimate driver compensation by presenting and evaluating several compensation schemes. Then, under a simplified assumption that the company's expenses and profit are proportional to driver compensation, a scaling factor is applied to compute the total TNC cost.

The notations used in this chapter are:

A	The arc set
a_s	The number of alighting passengers at stop s
α_0	The cost coefficient of per TNC vehicle hours
α_1	The cost coefficient of TNC vehicle operating time
α_2	The cost coefficient of TNC vehicle travel distance
α_3	The cost coefficient of per passenger served by a TNC vehicle
b_s	The number of boarding passengers at stop s
β	Fraction of TNC cost paid to TNC driver as compensation
d_{ij}	Travel distance of link (i, j)
$G = (N, A)$	Network G consists of node set N and arc set A
(i, j)	A tuple to describe a link between node i and node j
h	A virtual ending depot for TNC vehicles (only for formulation purpose)
M	A large number
m	The number of passengers for the truncated segments of a route
N	Node set
N_d	The set of passenger drop-off points
N_p	The set of passenger pickup points
o	A virtual starting depot for TNC vehicles (only for formulation purpose)
Q_k	The capacity of a TNC vehicle, ($Q_k = 3\ for\ the\ case\ study$)
q_j	The number of passengers to pick (> 0) or drop (< 0) at node j
R	The set of all fixed transit routes
r	A specific bi-directional transit route number, e.g., Route 91
S_r	The set of bus stops along route r
s	An individual bus stop
τ_{ij}	Travel time of link (i, j)
T_j^d	Required drop-off time for passenger j
T_j^p	Required pick-up time for passenger i
T_s	Starting time of TNC substitution operation
T_e	Ending time of TNC substitution operation
t_i^k	Decision variable indicating the time a TNC vehicle k arrives at node i
Θ	Objective function value
V	TNC vehicle set
w_i^k	Decision variable indicating the load of TNC vehicle k when it arrives at ɔde i
x_{ij}^k	Binary decision variable indicating whether vehicle k traverses link (i, j)
z_k	Binary decision variable indicating whether TNC vehicle k is used

4.1. Framework

To facilitate decision-making for transit agencies, we propose a framework, as shown in Figure 4-2. The data inputs from transit agencies include average bus ridership and the transit operating network and schedule, which are usually in the form of General Transit Feed Specification (GTFS). For every target route, a group of candidate truncation points is selected. When selecting candidate bus stops as truncation points, we need to consider two practical factors: whether intersections near the stops facilitate a turnaround for the bus and whether the bus stop allows for curbside pickup/drop-off of passengers. We suggest that transit agencies select stops that are next to a large parking lot or a roundabout, which allows buses to turn in the opposite direction easily. Going around a block with a left turn and three right turns or a right turn and three left-turns is also a possibility.

The next step is to calculate the cost of TNC substitution for each truncation point for comparison. We solve a static multi-vehicle pickup and delivery problem with time windows (m-PDPTW) that minimizes the total cost of hiring TNCs. To calculate the cost, we propose different types of contracts with different cost components and incorporate the contractual terms into the objective function. Other inputs for the optimization model include an estimation of non-transit-stop ODs of passengers and the network travel time/distance of TNC vehicles. Meanwhile, we calculate the fixed route cost reduction by multiplying the hourly operating cost components of fixed route buses (e.g., hourly wage for bus drivers, fuel cost, etc.) by the truncated segment lengths. Cost reduction from fixed route buses can be viewed as resources (both human and vehicle) that could be reallocated. The easiest reallocation would be to increase the frequency of operation segments on the same line where service is continued (as the round-trip bus travel time is less), as in the case of short-

turning. The buses and drivers can be reallocated to other routes' segments as well, though that would incur deadheading costs and would require more detailed scheduling and run-cutting optimization. In other words, the actual cost reduction from truncating the transit service can vary depending on how the resources are reallocated. This research does not focus on reallocation options and uses an overall cost reduction metric in the optimization, which is more appropriate for reallocation using higher-frequency short-turned services.

Once transit agencies determine the cost of TNC operations and the savings from removing fixed-route bus operations, they can decide whether, and on which segments, to replace fixed-route bus services with TNCs. The key step in the framework is to estimate the total TNC operating cost. In this step, we synthesize transit passenger origins and destinations, and we solve an m-PDPTW for minimizing the TNC cost.

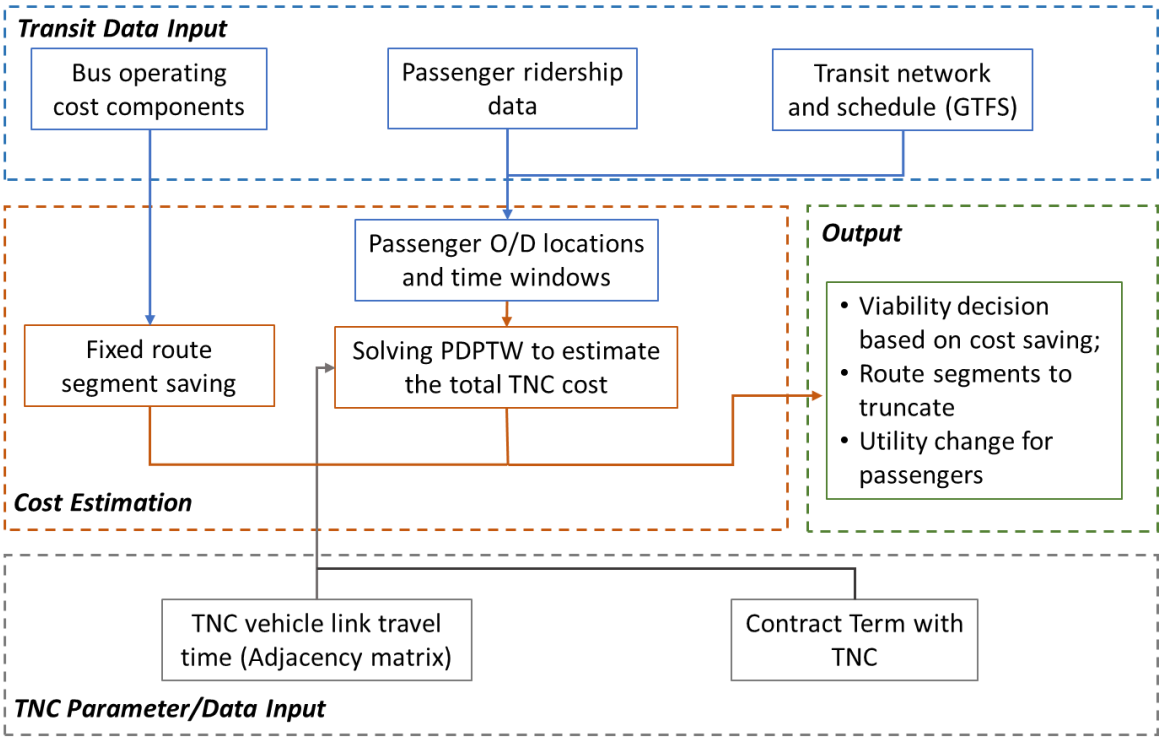


Figure 4-2: Modelling and decision framework

4.2. Generating Passenger ODs

This step generates a synthetic passenger population that matches the observed boarding/alighting passenger counts, so that synthetic spatial locations can be assigned to their origins/destinations, which then become pickup/drop-off points for the optimization formulation that models TNC vehicle routing. A transit agency operates several fixed-route buses within the service area. The set of routes is defined as $R = \{1,2,3, \dots, r\}$. Each route r is bi-directional and consists of a number of stops $S_r = \{0, 1,2,3, \dots, s\}$. The number of passengers boarding and alighting at a stop s are represented by b_s and a_s, respectively. Each passenger has an origin (O) and a destination (D) away from the stops they use (e.g., home location as the origin and office location as the destination). However, these true OD locations are typically not explicitly available to the transit agencies. The ridership data from transit agencies only indicates the number of passengers who board and disembark the bus. We approximate the passengers' OD locations by randomly selecting passenger locations within a service area defined by the maximum walking time/distance from the bus stops, using the walking distance rule set by the Federal Highway Administration (FHWA), wherein transit accessible walking distance should be a quarter to half of a mile (Nabors et al., 2008). The estimated walking speed of a person is suggested to be 4 ft/s or 1.2 m/s by Federal Highway Administration, the Federal Highway Administration (2006). Based on the accessible distance and walking speed, we draw an accessible area around the candidate truncation points. Within the accessible area, we randomly select OD locations for transit passengers and perform a Monte Carlo simulation to sample the required number of ODs. The process is shown in Figure 4-3, where the service area shown is indeed of a very unusual shape. The shape of the service area will be a circle in continuous

homogenous space like an open field allowing radial straight-line walking, and a perfectly symmetrical Manhattan grid will result in the area's boundary points forming a rectangular diamond centered on the bus stop. In practice, the street network characteristics such as the road layout, road density, barriers like large walled-off land-properties or rivers and streams can all affect the shape of the service area. A GIS analysis can easily yield the service area around any stop.

With the passenger OD locations assigned, we obtain the TNC vehicle network travel time through the Google distance matrix API. The travel time window (the earliest and latest time to arrive at a bus stop or home location) of each passenger is calculated by using the corresponding boarding/alighting bus time minus/plus necessary walking time from the OD location to the bus stop. The scheduled travel time setting guarantees that the passenger will not miss the bus that he/she originally would like to catch.

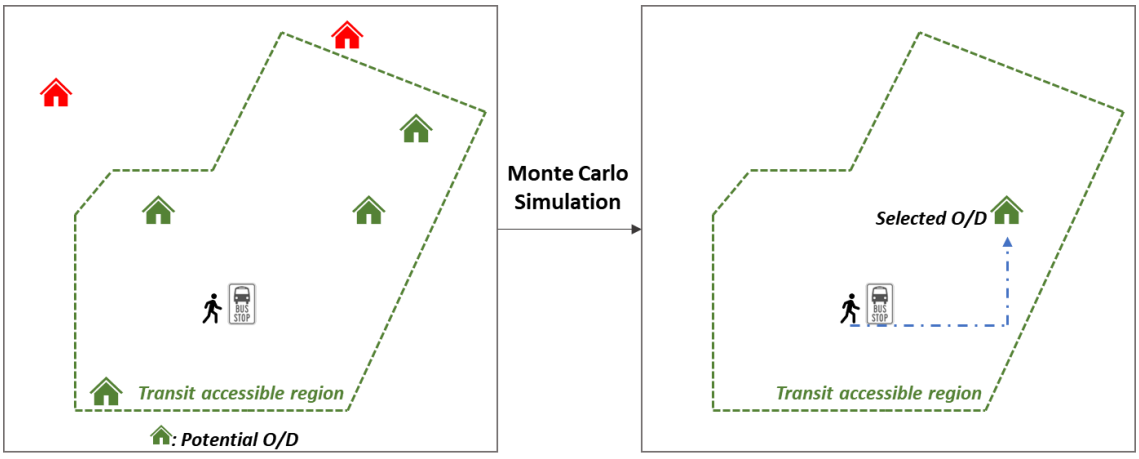


Figure 4-3: Generating transit passenger ODs

4.3. Estimating TNC Operation Time/Distance and Cost

The multi-vehicle pickup and delivery problem with time windows (m-PDPTW) is a vehicle routing problem in which each request involves multiple pickup locations that must

all be visited before a single delivery, and all visits must respect specified time windows. In this study, we adjusted the constraints so that each individual can have their own delivery location. To estimate the TNC cost, we define the m-PDPTW for serving passengers by TNC vehicles for each truncation point as follows. A network graph is defined as $G = (N, A)$, where N represents the set of nodes and A is the set of arcs. A passenger has a pickup node and a drop-off node within the truncation segment. Both the total number of pickup nodes and drop-off nodes equal the total number of passengers m. For formulation purposes, we label the passengers as $\{1,2, \dots, m\}$. The pickup node of a passenger i is labelled the same as the passenger index i, and the drop-off node of the passenger is labeled as $i + m$. The set of passenger pickup nodes and drop-off nodes are defined as $N_p = \{1,2, \dots i, \dots, m\}$ and $N_d = \{1 + m, 2 + m, \dots, i + m, \dots, 2m\}$ respectively. A link is defined as a tuple of nodes (i, j). The TNC vehicle set is defined as $V = \{1,2,3,4, \dots k\}$. Travel distance of the link (i, j) is defined as d_{ij}. For formulation purposes, a virtual outgoing depot and an incoming depot for TNC vehicles are defined as o *and* h respectively, which in reality do not need to be visited by any TNC vehicles. The objective is to minimize the total TNC operating time and mileage. Figure 4-4 shows an example of a m-PDPTW.

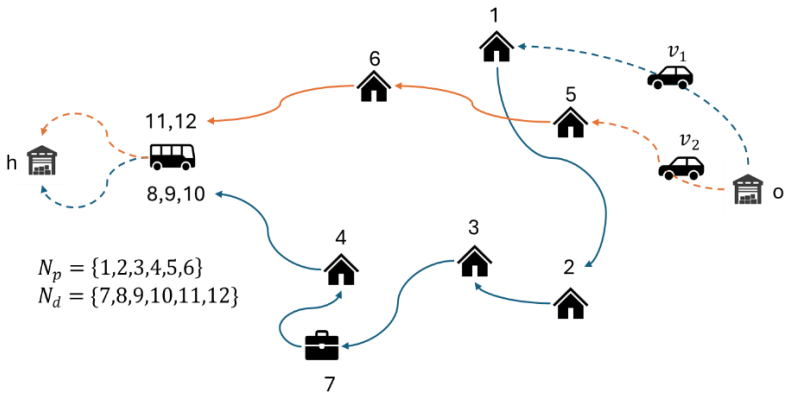


Figure 4-4: Example of m-PDPTW

We introduce the decision variables as follows:

x_{ij}^k: $Binary\ variable, equals\ 1\ when\ vehicle\ k\ travels\ the\ link\ (i,j)\ otherwise\ equals\ 0.$

z_k: $Binary\ variable, equals\ 1\ when\ a\ vehicle\ k\ is\ used, otherwise\ equals\ 0.$

t_i^k: $The\ time\ vehicle\ k\ arrives\ at\ Node\ i$

w_i^k: $The\ load\ of\ vehicle\ k\ when\ it\ arrives\ at\ Node\ i$

Model 1 (equation (4-1)) presents m-PDPTW for Estimating the TNC Total Cost:

$$\min_{x,z,t,w} \Theta = \frac{1}{\beta} \times \left[\alpha_0 \times \frac{T_e - T_s}{60} \sum_k z_k + \alpha_1 \sum_i \sum_j \sum_k \tau_{ij} x_{ij}^k + \alpha_2 \sum_i \sum_j \sum_k d_{ij} x_{ij}^k + \alpha_3 \sum_i \sum_j x_{ij}^k \right] \tag{4-1}$$

subject to:

$$\sum_{j \in N} \sum_{k \in V} x_{ij}^k = 1 \qquad \forall i \in N \backslash \{o, h\} \tag{4-2}$$

$$\sum_{i \in N, i \neq j} x_{ij}^k - \sum_{l \in N, l \neq j} x_{jl}^k = 0 \qquad \forall k \in V, \ \forall j \in N \backslash \{o, h\} \tag{4-3}$$

$$\sum_{j \in \{N_p\}} x_{oj}^k - \sum_{i \in \{N_d\}} x_{i,h}^k = 0 \qquad \forall k \in V \tag{4-4}$$

$$\sum_{i \in N} x_{ij}^k - \sum_{i \in N} x_{i,j+m}^k = 0 \qquad \forall j \in N_p, \ \forall k \in V \tag{4-5}$$

$$z_k \geq \sum_j x_{oj}^k \qquad \forall k \in V \tag{4-6}$$

$$t_j^k + M \cdot \left(1 - \sum_{i \in N} x_{ij}^k\right) \geq T_j^p \qquad \forall k \in V, \ \forall j \in N \backslash \{o, h\} \tag{4-7}$$

$$t_j^k \leq M \cdot \left(1 - \sum_{i \in N} x_{ij}^k\right) + T_j^d \qquad \forall k \in V \tag{4-8}$$

$$t_i^k + \tau_{ij} \leq t_j^k + M \cdot \left(1 - x_{ij}^k\right) \qquad \forall i, j \in N, \ i \neq j, \ \forall k \in V \tag{4-9}$$

$$t_i^k \leq t_{i+n}^k \qquad \forall i \in N_p, \ \forall k \in V \tag{4-10}$$

$$w_j^k + q_j \leq Q_k + M \cdot \left(1 - \sum_{i \in N} x_{ij}^k\right) \qquad \forall j \in N_p, \ \forall k \in V \tag{4-11}$$

$$w_j^k + M \cdot \left(1 - x_{ij}^k\right) \geq w_i^k + q_i \qquad \forall i, j \in N, \ i \neq j, \ \forall k \in V \tag{4-12}$$

$$x_{ij}^k \in \{0,1\} \qquad \forall i, j \in N, \ \forall k \in V \tag{4-13}$$

$$z_k \in \{0,1\} \qquad \forall k \in V \tag{4-14}$$

$$w_k \in Integer \qquad \forall k \in V \tag{4-15}$$

$$t_i^k \geq 0 \qquad \forall i \in N, \ \forall k \in V \tag{4-16}$$

The meaning of the objective function Eqn. (4-1) is as follows. For normal TNC operation, a passenger pays a pre-determined amount while requesting the ride, and the

amount is split between the driver that services the order and the TNC (e.g., Uber). The driver's compensation is usually calculated based on the total service time and/or distance (Uber, 2024). Following this compensation structure, we first calculate the compensation to drivers and divide the driver compensation by β to determine the total amount paid to the TNC platform. A generic contractual structure between transit agencies and TNCs could be written as the summation of the compensation terms divided by the TNC driver share fraction.

In Eqn.(4-1), $\alpha_0 \times \frac{T_e - T_s}{60} \sum_k z_k$ is the total vehicle-hour cost of TNC. $\alpha_1 \times \sum_i \sum_j \sum_k \tau_{ij} x_{ij}^k$ is the total operating hour cost. Similarly, $\alpha_2 \times \sum_i \sum_j \sum_k d_{ij} x_{ij}^k$ is the total travel distance cost, and $\alpha_3 \times \sum_i \sum_j x_{ij}^k$ is the compensation calculated based on the passenger count. In specific contract design, considering the complexity of contract terms and the redundancy of similar cost components, we limit the cost terms to be included in one contract structure to two. Based on the generic structure, we test seven different combinations of cost terms to quantify the compensation amount to drivers. The discussion with specific numbers continues in Section 4.5. In the discussion, we ensure that the compensation amount to drivers meets the minimum wage requirement and the minimum expectation of hourly income. We choose one representative cost structure and test out different β values to show the difference in total TNC contract values.

The meaning of the constraints are as follows. Eqn. (4-2) and (4-3) are standard routing constraints. Eqn. (4-2) requires every node to be visited once and only once. Eqn. (4-3) is the flow balance constraint for every node. Eqn. (4-4) ensures a TNC vehicle that enters the service also returns to normal TNC service after completing all tasks. Eqn. (4-5) ensures that if a passenger is picked up, the passenger must be dropped off at the designated

destination. Inequality (4-6) converts the links that are traveled to vehicle usage and gives the number of TNC vehicles used. Constraints (4-7) to (4-10) are time-window constraints. Inequalities (4-7) and (4-8) ensure that all pickup and drop-off activities fit the required time window, which is generated from the original passenger travel schedule. Constraint (4-9) is the sequencing constraint and also eliminates sub-tours. Constraint (4-10) ensures the drop-off activity of a passenger happens after the pickup activity. Inequalities (4-11) and (4-12) are occupancy/capacity constraints. Constraint (4-11) ensures that the vehicle occupancy will not be larger than its capacity at every pickup node. Constraint (4-12) tracks the load of vehicles at each node. Eqn. (4-13) to (4-16) are binary, integer and non-negativity constraints for the decision variables.

Equation (4-1), as a deviation of Pick-up and Delivery Problems (PDP), is NP-hard in nature. For small-scale scenarios, exact solvers, such as Gurobi, work well. However, for large-scale scenarios, obtaining the exact solutions is extremely computationally-intensive. In this study, to cope with the scalability of scenarios, we use Google OR Tool's neighborhood search and insertion meta-heuristics (Google LLC, 2023), to repetitively solve the PDPs. All our experiments are computed on a personal computer with an Intel Core i5-11300H CPU and 16 GB of RAM. The largest scenario has 306 passengers for which Google OR-Tool acquired an answer in 155 seconds.

In estimating the cost of TNCs and fixed route buses, the following assumptions are made:

1) Transit riders only pay the normal bus fare for the operation and do not pay extra for the truncated TNC service.

2) The fixed route bus truncations have been well broadcast to passengers, and passengers have indicated their pickup origin or drop-off destinations in advance.
3) Since the TNC substitution happens only in low-demand areas or non-peak periods for the context of this paper, we assume that the level of road network congestion is low; however, this assumption can be relaxed for higher demand conditions with appropriate single- or multiple-period trip time matrices without imposing any prohibitive computational burden.

Note that the optimization formulation above uses as input a set of pick-up and drop-off points. These points are passenger OD locations and stops on the transit lines. There is no assumption that all the transit stops need to be on one transit line. They can be on multiple lines, which is an important characteristic that leads to the formulation's flexibility. For instance, multiple truncated lines ending in a low-ridership area can have their outer segments replaced by TNC vehicles that carry out coordinated pick-up and delivery of passengers of those lines. In this case, the optimal vehicle routes will be found from single optimizations that include all the passenger demand points along with the truncation points of the multiple lines.

Instead of a short-turning-type truncation option, if transit lines traversing a low ridership area between two high-ridership areas (say, two satellite CBDs) are split into separate lines, the formulation can still be used for optimizing the TNC operations in the area, as the points for pick-up and delivery are still well-defined. The same TNC vehicles contracted for that area can serve as feeders to the transit lines, and even for connecting the few through passengers with two transfers between the split. Such flexibility for application to a variety of contexts is a hallmark of the formulation.

The next chapter examines the application of the optimization framework to various kinds of TNC operations, including those described above. The remainder of this chapter only considers the truncation of lines at stops beyond which the ridership is low for the rest of the lines.

4.4. Numerical Case Study in the City of Long Beach

To assess the impact of substituting TNCs in low-demand areas and during off-peak hours, we conduct a numerical case study in the City of Long Beach, California, focusing on the bus system operated by Long Beach Transit (LBT).

We estimate transit demand using the 2020 ridership data provided by LBT. For our analysis, we use both stop- and trip-level daily ridership data averaged over a service period as our passenger ridership input. The data indicate that the downtown area is a high-demand area, and the demand decreases as the distance from downtown increases. Additionally, we obtain LBT's fixed-route bus network data from the General Transit Feed Specification (GTFS) files. Using GIS software, we merge the LBT transit network with the road network and load the ridership data to the corresponding stops and trips. This results in a dataset containing trip information and ridership by bus segment, which forms the basis of our analysis. Figure 4 presents all LBT bus stops on a road network. LBT operates 30 routes with 1,727 stops. In this chapter, off-peak hours are defined as times before 7 AM (early morning) and after 7 PM (evening). Off-peak trips are those trips that reach their farthest stop from downtown before 7 AM or after 7 PM.

Truncating bus routes is not operationally feasible at every stop, as buses require specific physical attributes, such as a turning point to change direction and shorten their path. Suitable truncation points are typically located near intersections (or parking lots)

where they have sufficient spaces to allow for TNC curbside pickup/drop-off. Transit agencies may also consider additional physical and traffic attributes when determining feasible truncation points. We begin by filtering out stops where bus turning is not feasible. We then identify candidate truncation points along the bus route, selecting stops near intersections on both sides (forming a pair). Due to the city's layout, most transit routes operate between suburban regions (low demand) and downtown (high demand). Therefore, without losing generality, we truncate bus operations on the low-demand end of the route. In cities where routes have two low-demand ends, it is also possible to truncate the operation on both ends.

Figure 4-5 illustrates five examples of candidate truncation points for Route 93. In Long Beach, the northern area and regions farther from downtown typically have lower ridership. To implement TNC substitution, we eliminate all stops beyond the truncation point in both directions and provide coverage via TNC vehicles. The figure demonstrates how each subsequent truncation point removes additional stops from the bus route, increasing TNC vehicle coverage in those areas.

We use an average bus operating cost of $171 per hour in this study for LBT, which is calculated based on the operating expenses and annual operating hours presented in the (Federal Transit Administration, 2022). The financial report is the most recent one by LBT.

In the following sections, we first continue our discussion on TNC compensation contracts. Using a selected contract structure, we collect data points by calculating the total costs for both TNC services and fixed-route bus operations across various candidate truncated segments. Subsections 4.6 and 4.7 compare cost savings and passenger disutility across several scenarios.



Figure 4-5: Long Beach Transit Stops and Examples of Truncation Candidates

4.5. TNC Compensation Contract and Bus Cost

We continue the discussion of compensation plans for TNC service from Section 4.3. In previous studies, a compensation scheme for TNC is usually designed based on vehicle mileage, service duration, and the number of passengers served. However, it is difficult to obtain specific parameter values and exact compensation structures from TNCs. Usually, TNCs calculate fares for passengers based on a minimum charge, travel time and/or distance, and demand surcharge, which could be adopted to calculate driver compensation (Uber, 2025). Previous studies on transit-TNC partnerships also rarely released specific parameter values. One recent report by the City of Minneapolis(Minneapolis, 2024) suggests three different compensation structures (contract types A, D and E in Table 4-1) for transit-TNC integration. Together with the four structures, we propose a total of seven different

compensation structures for comparison. From a transit agency perspective, a designated scheme should (1) fulfill the minimum wage requirements by law, (2) meet the minimum hourly income expectation for drivers to ensure driver participation, and (3) save cost for transit agencies. Table 4-1 shows the seven compensation structures we proposed and each row suggests a cost calculation based on different factors. Each factor is actually a coefficient of a term (α_0 *to* α_3) in equation (4-1). We can adjust the optimization and use combination of the terms to reflect the different compensation schemes.

Table 4-1: TNC Compensation Schemes

Type	vehicle*hour α_0	Minute α_1	Mile α_2	Passenger α_3
A	24			
B	10	0.25		
C		0.5		
D		0.34	1.17	
E		0.51	1.4	
F		0.42	1	
G		0.25		1.5

First, we would like to ensure that the proposed compensation meets the average expectation of hourly income for drivers and satisfy the minimum wage requirement of $16 per hour (State of California, 2024). Besides the minimum wage, we estimate driver income expectations using the following formula:

$$minimum\ wage + \frac{gas\ price\ *\ avg.speed}{avg.vehicles\ mpg} + maintenance\ cost\ = total\ payment \qquad (4\text{-}17)$$

We obtain the value for the average gas price ($4.63 per gallon) from the AAA gas price website (American Automobile Association, 2024), average travel speed (25 miles/hour) from a report of (City of Long Beach, 2023), average vehicle fuel economy (25.4 miles per gallon) from the Alternative Fuel Data Center (U.S. Department of Energy, 2025)

and the average cost of car maintenance ($0.0983 per mile) from a report (Betterton, 2024) . Correspondingly, we could estimate the driver's hourly expectation as:

$$16 + \frac{4.63 * 25}{25.4} + 0.0983 * 25 = \$\,23.02 \quad (4\text{-}18)$$

Our analysis suggests that a rate of $24 per hour (Contract A) is sufficient and potentially superior to current TNC driver compensation rates. The City of Minneapolis has a minimum wage of $15.57 per hour, which is comparable to California's minimum wage. The study conducted in Minneapolis shows that Contract A tends to yield the lowest compensation for TNC drivers, indicating that both Contracts D and E meet or exceed the $24 per hour expectation. Using Contract A as a benchmark, we adjusted parameters in the proposed contracts to ensure they satisfy the three key requirements for driver compensation.

Contracts D, E, and F base driver compensation on "effective service time," meaning the time a vehicle spends transporting a rider and the empty duration/mileage when the vehicles move between rides, while Contract A compensates drivers based on "total in-system time", including idle times. Contract B combines both approaches. Similarly, in Table 4-1 "vehicle*hours" refers to compensation based on in-system time, and "minute" refers to compensation based on actual service time.

Applying the cost structures and parameters from Table 4-1 to Optimization Model 1 (Eqn. (4-1)), we calculate the total compensation for drivers by setting the β value to 1, which is equivalent to assuming the extreme case of all of the payment to TNC being used for driver compensation. Using Route 93 as an example, Figure 4-6 compares driver payments under different cost structures.

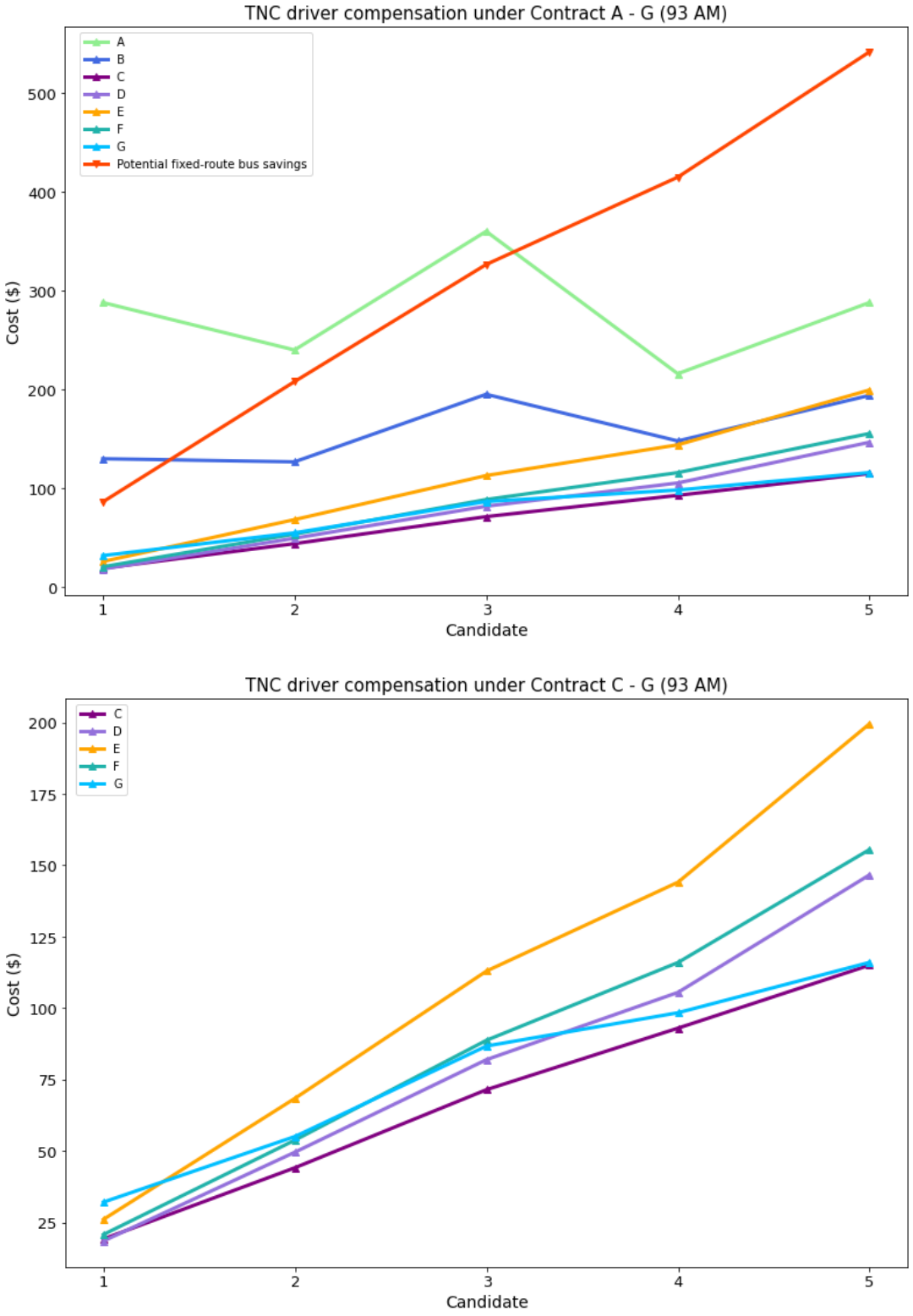


Figure 4-6: Comparison of Contract Types

(Upper: all types; Lower: zoom-in for type C – G)

As shown in Figure 4-6, our calculations indicate that all the proposed contracts guarantee drivers the minimum income expectation of $23.02 per hour (well above the minimum wage), demonstrating the fairness of these contract designs. Comparing driver compensation with potential bus savings, we find that for most candidate truncation points, driver compensation remains lower than potential fixed-route bus savings (the red line), suggesting cost-saving potential for LBT. The exceptions are the first two candidate truncation points under Contract A and the first point under Contract B. This is because Contracts A and B use a rounded-up hourly based rate on total in-system time, which based on the study area and parameters assumed here is less cost-efficient than actual service time, and the truncated bus segments are not long enough to offset the fixed-route bus costs to achieve breakeven.

Additionally, the inconsistent trend in Contracts A and B is attributed to the location of rider demand and the tight time window requirements. For instance, at truncation point 3, there may be requests that a single TNC vehicle cannot accommodate within the required time window, necessitating additional vehicles. As a result, Contracts A and B may lead to higher TNC costs, with vehicles remaining idle for parts of the time, making them less cost-efficient for transit agencies. In contrast, Contract E tends to offer higher driver compensation in most cases. For the remainder of this study, we adopt Contract E as it reflects an average trend and demonstrates the robustness of the TNC substitution model.

As noted in Section 4.3, these compensation schemes are calculated only for drivers; however, TNC platforms also take a share of the driver's income as commission. To estimate the total amount payable to TNCs, we divide the amount paid to drivers by β to determine the total compensation or contract amount. The higher the fraction of $1-\beta$, the greater the

TNC's share of the total compensation, increasing the amount transit agencies must pay. In this study, we consider six levels of $1-\beta$ ranging from 0.2 to 0.7 (20% to 70% share for TNC company) to demonstrate the calculation of total costs.

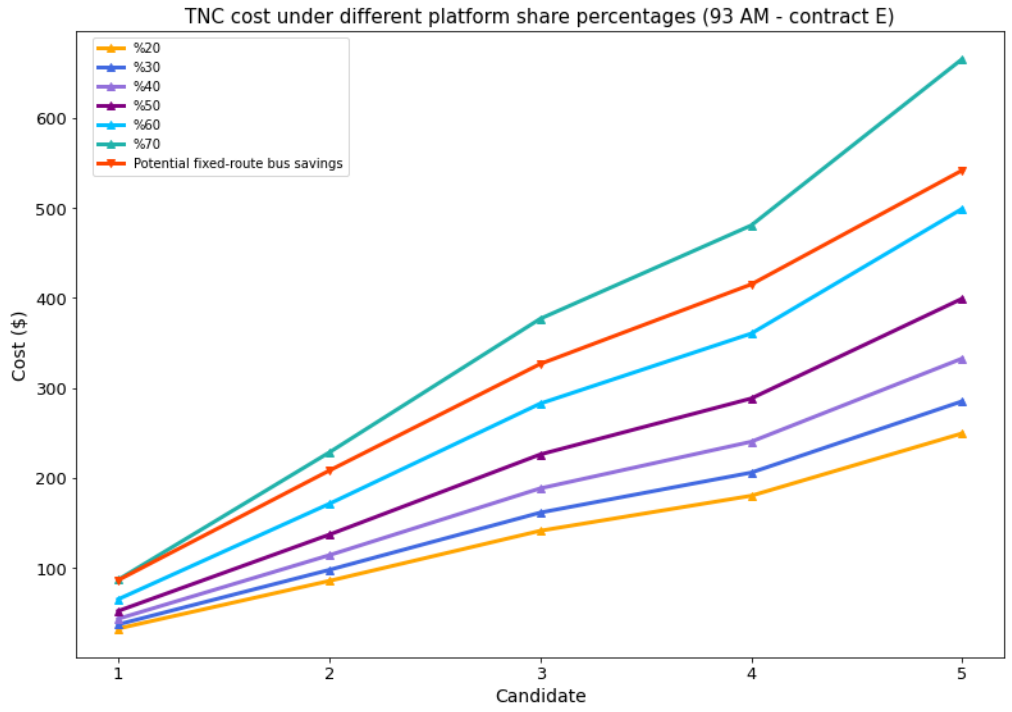


Figure 4-7: Comparison among Different TNC Share Percentages (β from 0.2 to 0.7)

Figure 4-7 illustrates the impact of various TNC share percentages ($1-\beta$ *fractions*) on total compensation, including payments to both drivers and the platform. Unsurprisingly, as the TNC's commission increases, the partnership becomes less financially beneficial for transit agencies. The breakeven point for Contract E is identified at around 65%. In practice, the exact percentage of commission is typically unknown to both drivers and the public. For the purposes of Model 1 and further discussion, we assume a 40% platform share (equivalent to $\beta = 0.6$), though this percentage may still be relatively high compared to typical real-world practices.

The rides occur during low-demand periods and in areas where independent TNC requests are unlikely. By partnering with transit agencies, drivers are guaranteed additional scheduled rides, even when market demand is low. Two scenarios may arise under this arrangement. In the first, if only one or a few rides are scheduled, the driver can leave the service area after completing those trips to pursue other opportunities. In the second, if multiple rides generate a demand frequency comparable to regular service, drivers are compensated for idle time and empty mileage between trips. In both cases, the compensation structure proposed in this study provides earnings per unit of operating time comparable to those of drivers working independently outside the contract.

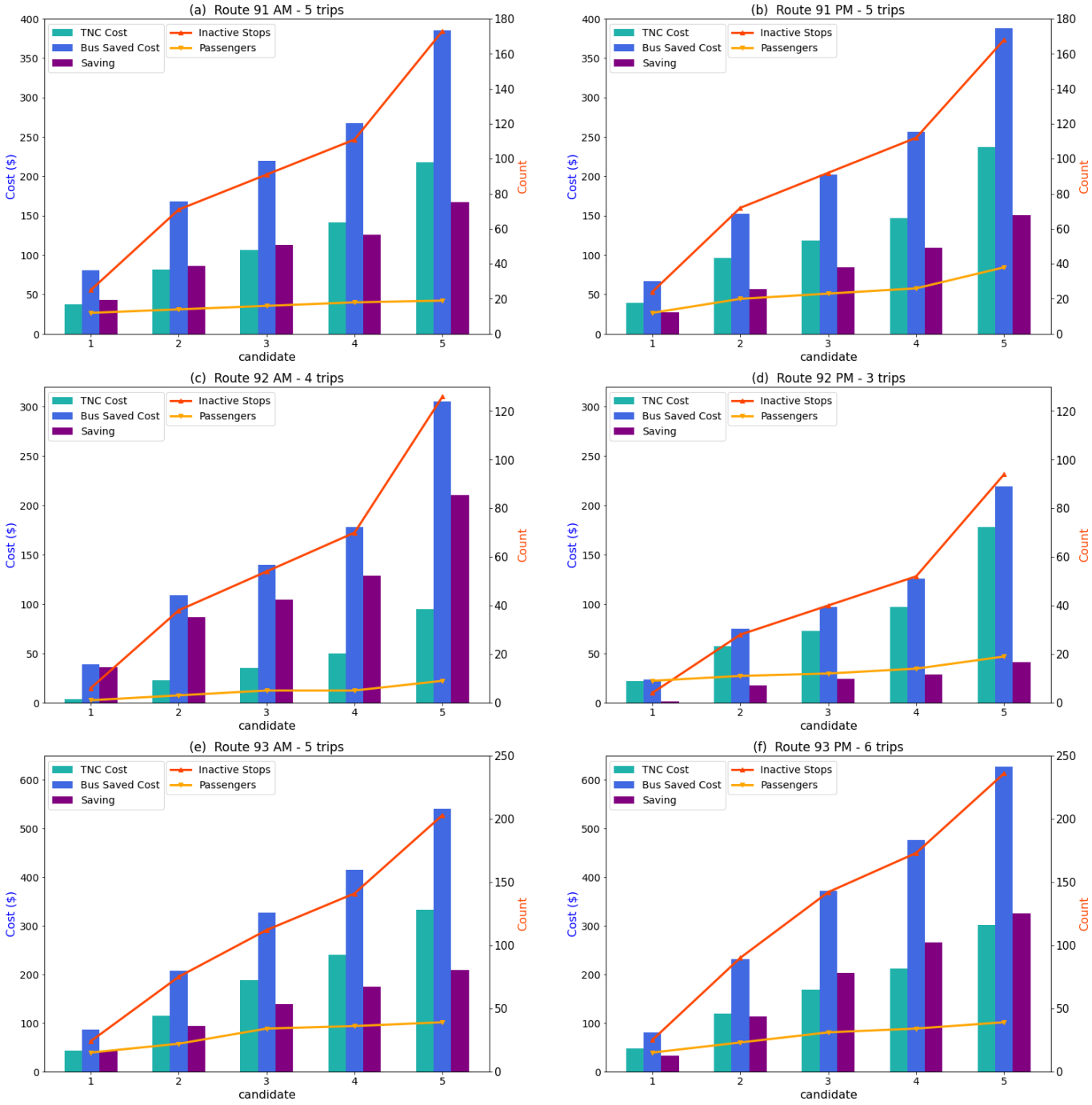
4.6. Cost Savings from TNC Substitution

In this section and the next one, we evaluate different metrics for TNC substitution using specific route examples from Long Beach Transit (Routes 91, 92, 93, and 192). The analysis in this section focuses on the potential cost savings for individual routes in the early morning and late evening service periods. For each route, we select 5 candidate truncation points and apply the contract structure and parameters of Type E, with a reasonable 40% TNC share, to calculate the total TNC contract cost.

The truncation points are chosen based on operational feasibility, particularly near major intersections with adequate options nearby for turning the bus around. For each route, Candidate 1 is the farthest truncation point from the downtown stop, located closer to the low-demand end of the route, while Candidate 5 is the nearest to the downtown stop.

Figure 4-8 summarizes different types of cost, total savings, the number of inactive stops, and the number of passengers in each truncation segment. Based on the criteria of a viable TNC substitution, transit agencies may choose any truncation point that has total

savings larger than zero (the breakeven point). In practice, transit agencies may combine multiple factors, such as cost savings, budget scope, project scope, and additional bus operational requirements, to make decisions.



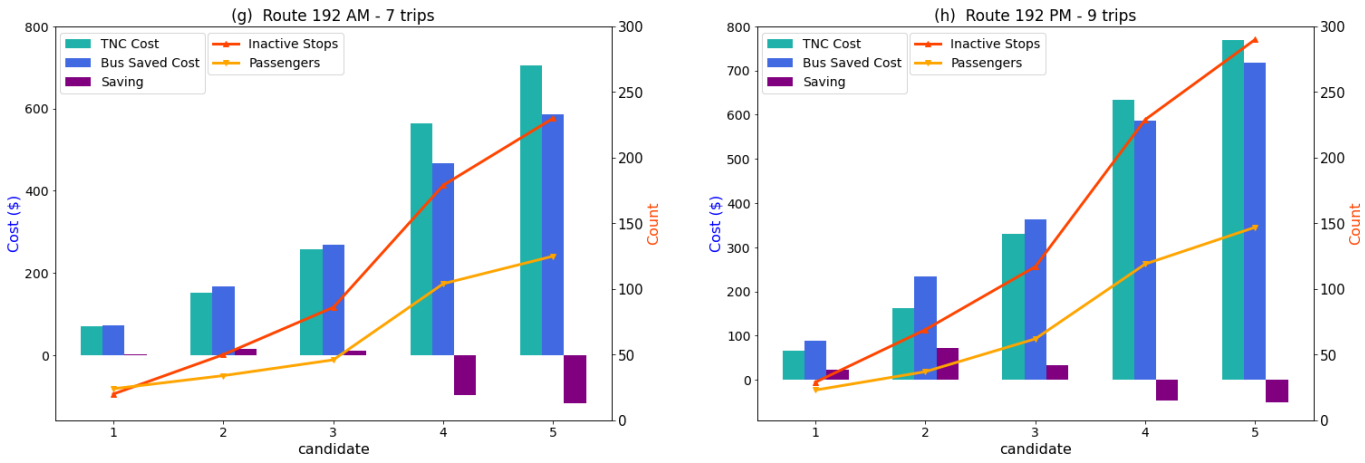


Figure 4-8: Cost and savings of TNC substitution for selected routes

Across all subplots, TNC cost (green bars) and potential savings from fixed-route truncation (blue bars) increase linearly with the number of inactive stops (red lines) and the number of passengers (orange lines) in the truncation segment. However, the overall savings (purple bars) vary significantly between different routes and time periods. First, though early morning and evening are both off-peak periods, the effectiveness of TNC substitution is not identical. Second, within the same period, the trend of savings can differ. The analyses of individual routes are as follows.

For Route 92 and, to a lesser extent, Route 91, TNC substitution is more effective in the early morning period than in the evening. For routes 91,92, and 93 in the morning and evening (subplot a-f), all five candidates achieve cost savings for LBT, with Candidate 5 achieving the highest total savings. For Route 93 in the late evening (subplot f), TNC substitution is the most effective among the 4 routes, largely due to the low ridership compared to the number of truncated stops which is again consistent with the results of the

previous section. LBT could consider extending the truncation segments closer to downtown for even greater cost savings.

The situation for Route 192 (morning and evening) differs from other cases. For most candidates, the cost savings are minimal or even negative, suggesting that replacing the bus service with TNCs may not be beneficial. This outcome is likely due to the high number of passengers per truncated stop, making the bus a more efficient and viable option. In other words, the bus remains productive and cost-effective because it serves a sufficient number of passengers. Among the candidates for Route 192, Candidate 2 achieves the highest savings and emerges as the best option. However, beyond Candidate 2, the truncation segment extends further, increasing TNC costs as more passengers require TNC service. This rise in TNC expenses ultimately diminishes the overall savings.

While total cost savings are a critical factor for financial sustainability, transit agencies may also weigh other criteria while choosing truncation points. For instance, shorter truncation segments may be more cost-effective, but slightly longer segments could serve more passengers (e.g., comparing Candidate 2 to Candidate 3 in subplot h). Since passenger utility is another key evaluation metric, it is important to compare changes in total passenger utility with and without TNC substitution.

4.7. Passenger Disutility

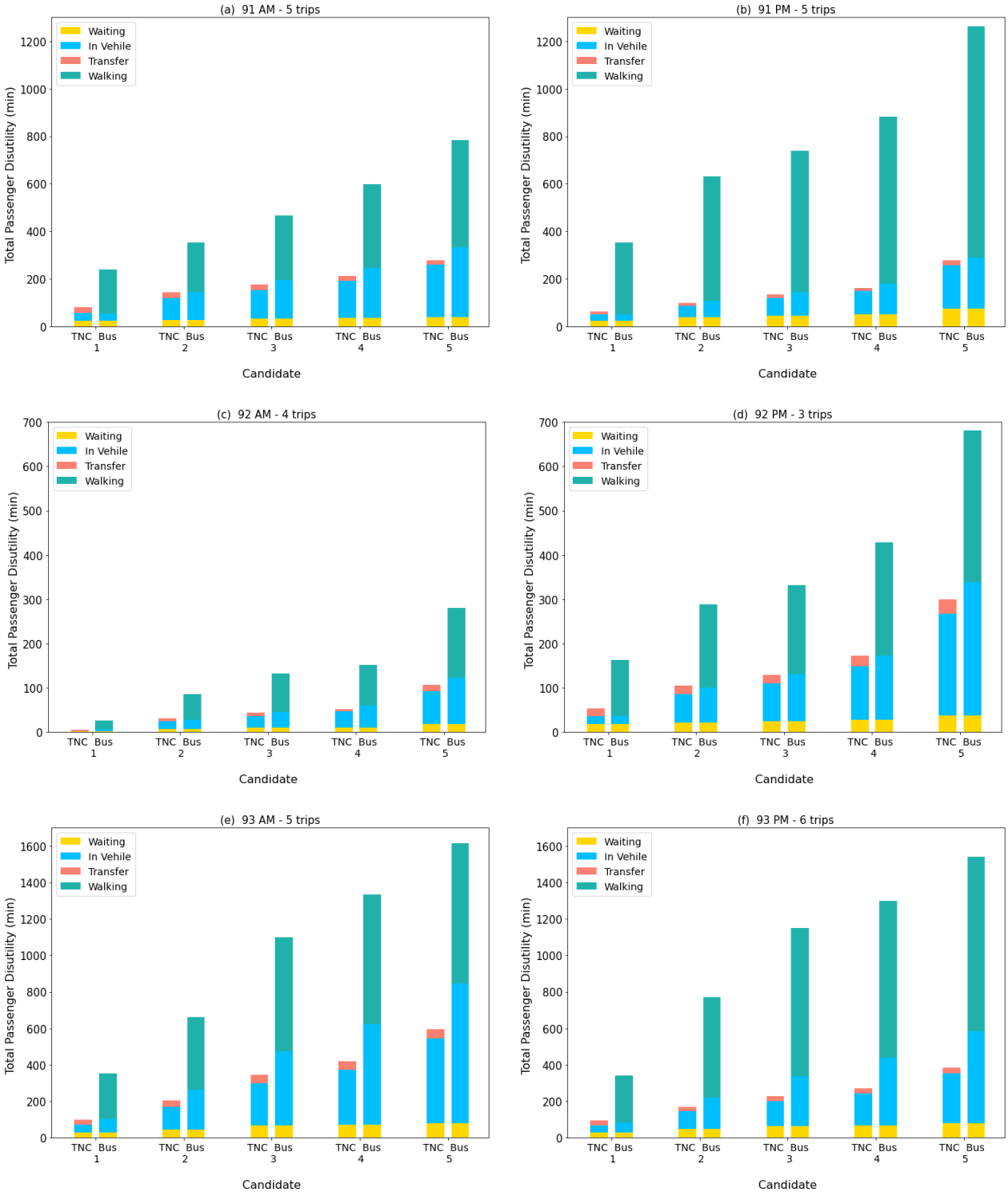
In addition to comparing costs, we also evaluate changes in passenger travel disutility before and after TNC substitution. Passenger travel disutility includes components such as walking, waiting, in-vehicle travel, and transfer disutility and is measured by the value-of -time. We calculate each type of disutility based on the time spent on the corresponding activity, using in-vehicle travel time as the benchmark. Specifically, one minute of in-vehicle

travel time equates to one unit of disutility. According to (Qiu et al., 2015), walking and waiting time are respectively 3 times and 2 times as costly as in-vehicle travel time. We apply these same ratios when calculating disutility for both buses and TNC vehicles. Additionally, we set the disutility for each transfer between a bus and a TNC vehicle to be equivalent to one minute of waiting time. We assume that passengers are aware of the schedule of buses and arrive at the bus stop only one minute before the bus arrival to minimize their waiting time at the bus stop.

Figure 4-9 compares total passenger disutility for the five truncation-point candidates on different routes. Overall, the figure shows that TNC substitution significantly reduces passenger travel disutility, as the total disutility decreases across all candidate truncation points. This reduction ranges from 60% to 75%. The largest portion of disutility reduction is from walking, as TNC services provide direct connections between truncation points and destination locations, minimizing walking time, which carries the highest disutility. The trade-off for reduced walking time is an additional transfer between buses and TNC vehicles, but this incurs much lower disutility than walking. In all cases shown in Figure 4-9, TNC substitution results in lower in-vehicle travel disutility than buses, though the difference is minor. This is because shared TNC vehicles make detours to pick up or drop off multiple passengers.

As we suggested in the previous subsection, the decision for truncation point selection should be based on both cost and passenger disutility. For example, consider Candidates 2 and 3 in subplot (h) of both Figure 8 and Figure 9. Candidate 2 saves an extra $40 than Candidate 3. However, Candidate 3 serves an additional 25 passengers and

generates 700 more units of disutility reduction. Overall, Candidate 3 could be a better option than Candidate 2.



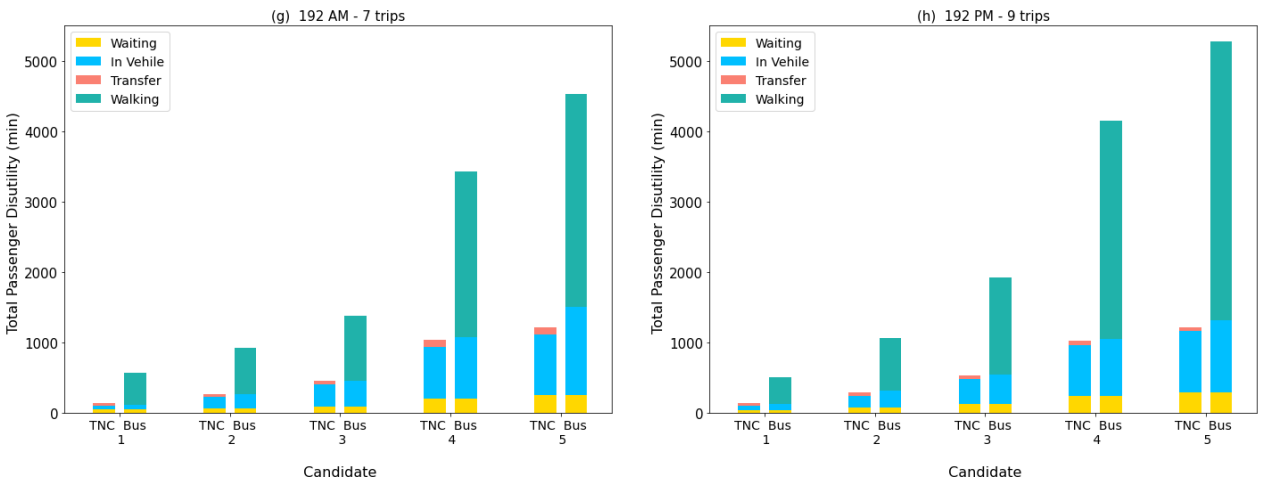


Figure 4-9: Passenger Disutility Comparison

This chapter shows that replacing low-demand bus segments with door-level shared TNC service can improve both system efficiency and passenger experience. Results from the Long Beach case study indicate that, for many routes and off-peak periods, TNC substitution leads to meaningful operating cost savings while reducing passenger travel disutility by 60–75%. The largest gains come from eliminating walking and providing more direct trips, with only minor increases in in-vehicle travel due to sharing. Overall, the findings suggest that targeted use of TNCs can be a practical and effective strategy for serving low-demand areas without reducing service quality.

CHAPTER 5: Comparison of Different Service Designs

In chapter 4, we presented a TNC operation model in partnership and contract with transit agencies, targeting the low-demand truncated segments of a targeted route with a door-level service, which we considered as the benchmark design in this section. The benchmark design ensures that passengers are efficiently transported between designated truncation points and their precise home or work locations.

In this chapter, we investigate the feasibility of service area adjustment:

1) Low-demand middle segments
2) Multiple-route truncation
3) Effect of bus frequency
4) Effect of bus stop density

We show how our methodology and partnership can function under these adjustments. Later in this chapter, we compare the benchmark design versus three alternative services:

5) TNC substitution with stop-level service, where TNC vehicles only transport people between bus stops (Similar to chapter 3 but with the optimization method of chapter 4).
6) Non-cooperation between transit agencies and TNCs, where no contract agreement is reached between them.
7) Demand Responsive Transit (DRT), where the DRT vehicles are owned by transit agencies and provide substitute services to fixed-route buses.

We evaluate the impact of these service alternatives on overall operating costs and passenger disutility, with a focus on determining whether they offer advantages over traditional bus services or the proposed contracted TNC operations.

5.1. TNC Operation in Low-demand Segments in the Middle of the Route

An important factor to consider when identifying unproductive segments is the number of passengers on board. Even if the middle segments have few pickups or drop-offs, we must still account for passengers traveling through those sections between high-demand areas. Our framework is still applicable to these scenarios. There are also cases where a sufficient number of middle segments may have consistently low ridership. Figure 5-1 illustrates an example of these routes with intermediate low ridership segments. In such situations, it is possible to truncate these unproductive segments, serve them with TNC vehicles, and operate two separate bus routes at each end. The optimization model and algorithm remain unchanged; the only modifications involve the pickup and drop-off locations, which may include bus stops, and the time windows, which are determined by the schedules of the active bus routes on both ends.

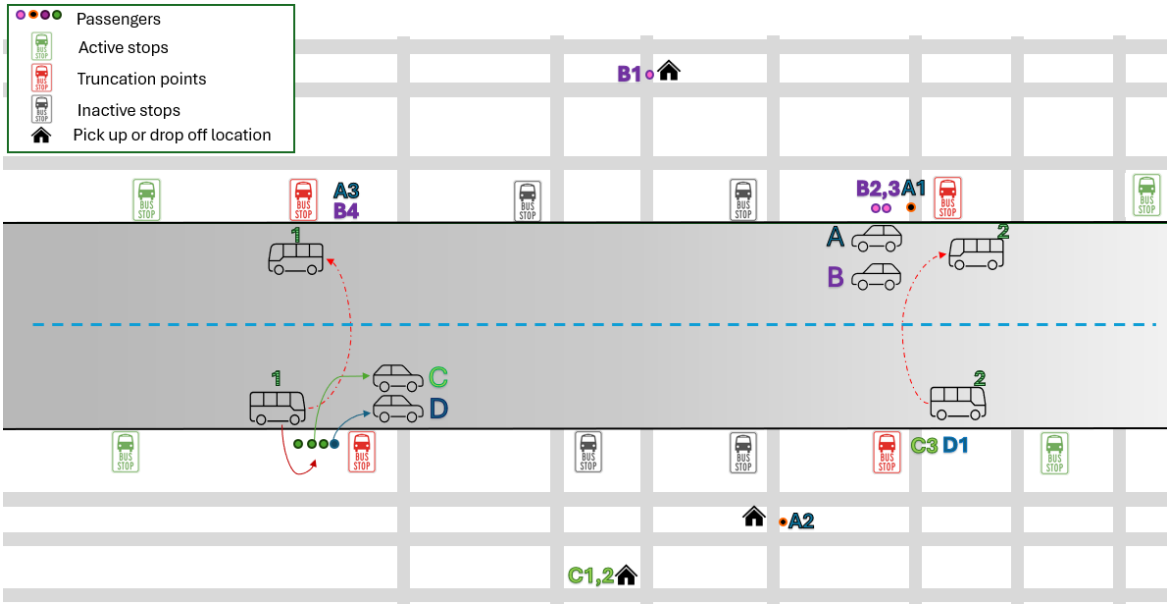


Figure 5-1: TNC operation in the truncated intermediate segments

5.2. Parallel TNC Service vs Combined Operation on Neighboring Routes

In cases where several routes contain low-productivity end segments, an agency may opt to truncate all of them. The associated TNC substitution service can be configured in one of two ways: (1) a unified ride-matching process in which TNC vehicles can serve passengers across all truncated routes, or (2) independent substitution services where each route is served separately. In many urban transit networks, bus routes often operate in parallel along adjacent streets, converge at a limited number of stops, or run in close proximity for portions of their alignments. In such cases, sometimes ridership patterns during off-peak hours may reveal redundancies that motivate transit agencies to consider truncating multiple routes. While the operational strategy proposed in this study is feasible on a route-by-route basis, this section explores a combined approach. Specifically, we examine a scenario in which all parallel routes are truncated, and a single TNC service is introduced to provide connectivity across them. This integrated operation allows vehicles to circulate between routes and potentially form more efficient trip chains. Figure 5-2 illustrates this case for the Long Beach bus network, focusing on Routes 91, 92, and 93, which operate in close proximity near their endpoints.

An important question in designing such an integrated operation is determining where routes should be truncated to enable TNC vehicles to provide the most effective combined service. As discussed earlier, the precise truncation points are highly dependent on the physical characteristics of stops, particularly whether buses can easily reverse direction and re-enter service. In the context of combined operations, one promising approach is to identify the closest stop pairs across different routes, thereby allowing TNC vehicles to transfer more efficiently between them. However, the closest pairs may not

always represent the optimal choice. The spatial distribution of demand and the passenger load along each route can significantly influence the most suitable truncation points. As in Chapter 4, the cost, passenger utility, or other relevant performance metrics can be evaluated for different truncation pair combinations to determine the most effective configuration.

Table 5-1 presents a comparison of individual route services and the combined service for Routes 91, 92, and 93 during the early morning period when the ridership is low. Each route has five candidates, numbered so that candidates with the same number are located near each other across routes. The combinations of truncation options are in the first column.

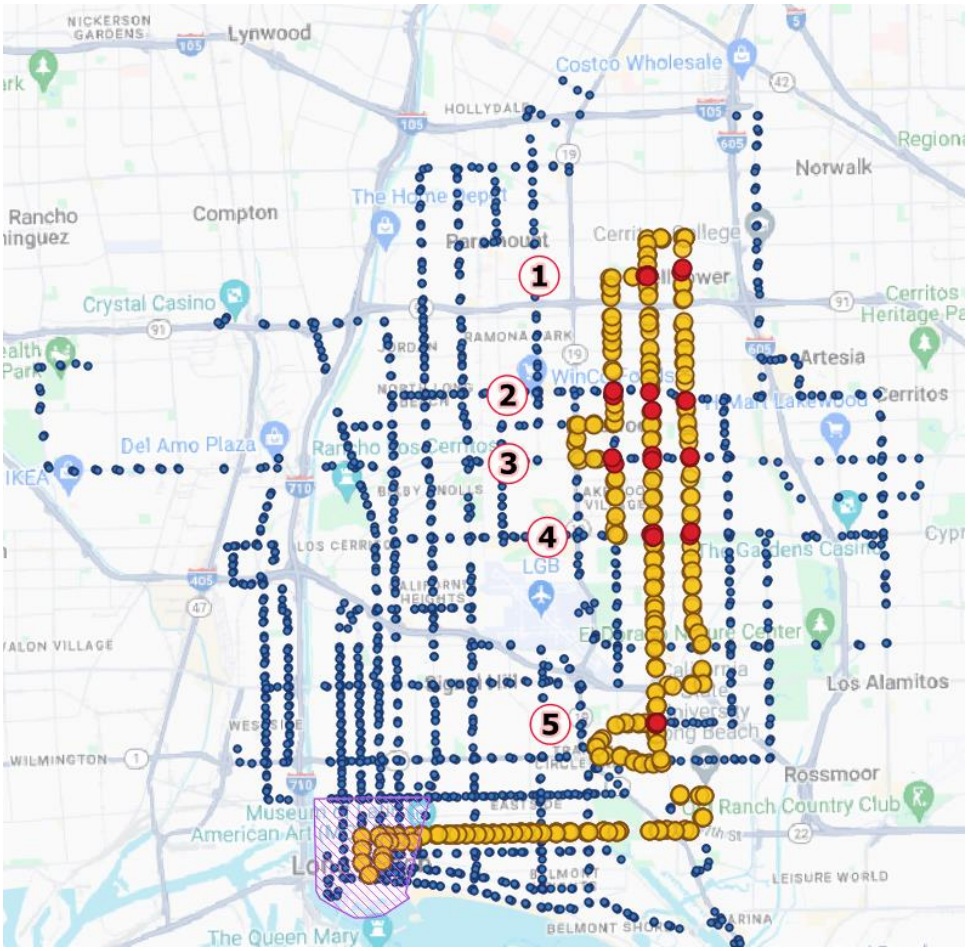


Figure 5-2: Routes 91,92, and 93 Long Beach transit

Table 5-1: Comparison of individual route operation vs. combined operation

91,92,93	Inactive stops	Passengers	Combined		Independent		Saved bus cost ($)
			min #vehicles	min TNC Cost($)	min #vehicles	min TNC Cost($)	
1,1,1	55	28	11	80.57	13	80.57	206.31
1,2,1	87	30	14	100.78	14	100.78	276.25
2,1,2	152	37	13	191.86	16	192.55	415.13
2,2,2	184	39	14	211.99	17	212.77	485.07
2,2,3	221	51	12	294.83	13	295.60	603.54
3,3,3	257	55	6	333.50	14	333.50	685.57
4,3,3	277	57	11	367.57	14	367.57	733.59
4,4,4	322	59	10	432.31	13	432.31	860.19
5,4,5	446	63	12	604.39	15	604.39	1104.15
3,4,5	364	60	15	493.07	15	494.78	938.85
5,5,5	502	67	11	636.61	14	651.26	1231.20

Table 5-1 demonstrates that the combined service can result in reduced operating costs. In addition, because routes share TNC vehicles under this configuration, the minimum number of vehicles required is lower. Notably, the lowest operating cost does not always coincide with the minimum fleet size, but this outcome highlights the flexibility offered by the combined service design. The cost savings, however, are not substantially greater than those achieved under the individual service scenario. This limited improvement may be attributed to factors such as the spatial separation of routes in certain areas, strict passenger time-window constraints, and the assumption of zero waiting time.

Among the candidate combinations, those with equal truncation points across routes tend to reduce vehicle requirements. Nevertheless, with the exception of the final case (5,5,5), these configurations do not yield a significant cost advantage. The improvement observed in the last case arises from the fact that all routes converge at the same stop,

enabling them to share truncated pairs. This arrangement allows a greater proportion of TNC vehicles to meet at a common location and transfer between routes without operating empty. Another contributing factor is the presence of longer route segments, which introduce slightly greater flexibility in time windows and improve coordination.

5.3. Effect of Bus Frequency

Having low ridership during off-peak hours is a strong indicator of low productivity; however, the frequency of bus service prior to substitution may also play a significant role in determining the feasibility and cost-effectiveness of using TNCs. To better understand this relationship, we evaluate two different bus frequency scenarios using the same passenger set and the same origin–destination pairs, allowing us to isolate the impact of service frequency on the resulting TNC costs. Figure 5-3 illustrates this process on truncated route segments in an example route, with boarding and alighting activity shown for each stop and for both inbound and outbound trips.

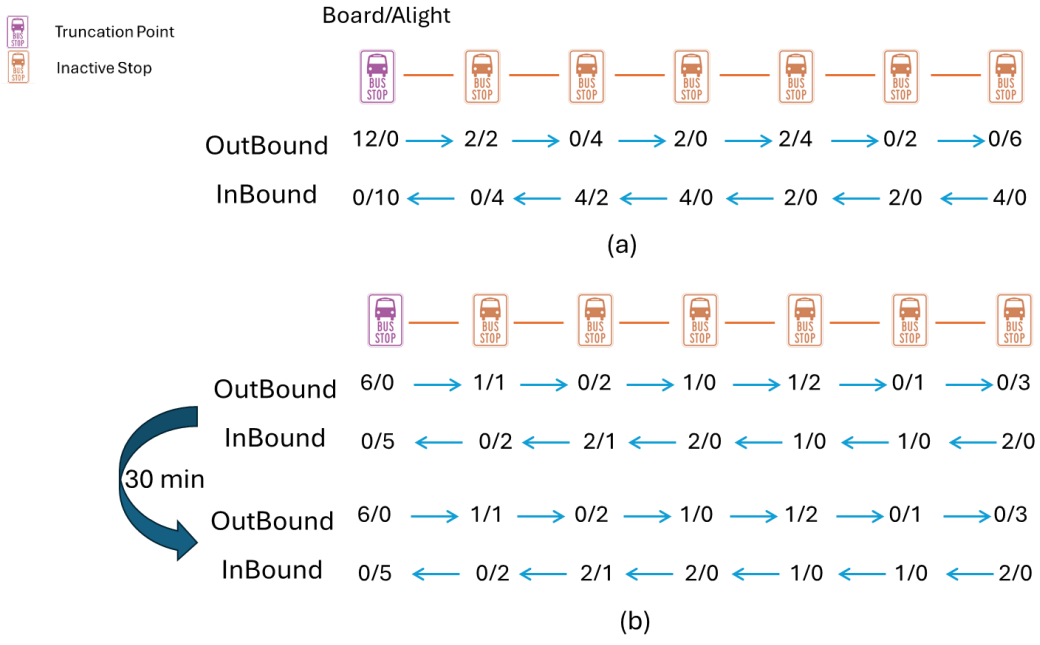


Figure 5-3: Example route with 2 different bus frequencies

In subplot (a), Case 1, all passengers are assumed to board and ride the same bus trip, meaning they will all be handed off to TNCs at the same time. In subplot (b), Case 2, the same passengers are distributed across two bus trips: half board the first bus and the remaining half board the subsequent bus, which arrives 30 minutes later. In this case, passengers' time windows are adjusted accordingly to reflect the staggered arrival times, enabling us to explore how passenger distribution influences TNC scheduling and cost outcomes.

Table 5-2 presents the quantitative results of the truncation and substitution analysis for these bus segments. As shown in the table, increasing bus frequency doubles the operating cost while the total number of passengers served remains constant. This outcome highlights that, beyond the total demand observed during the study period, the distribution of passengers across individual bus trips plays a critical role in overall productivity. When frequency is high in a low-demand time or area, riders are dispersed among multiple trips, resulting in fewer passengers per bus and disproportionately higher operating costs per rider. Although the number of TNC vehicles required remains the same across scenarios, the total TNC cost increases slightly in the higher-frequency case. This occurs because passenger arrivals are split across two approximate time windows, requiring two rounds of TNC trip assignments to serve the full passenger set rather than a single consolidated set of trips.

In such cases, agencies often consider reducing the number of bus trips to better match demand; however, service frequency may already be at the minimum acceptable level based on equity considerations or may be required to meet commuting patterns in the corridor. When further reductions are not operationally or socially feasible, substituting the low-productivity fixed-route segments with TNC service becomes a financially advantageous alternative. By reallocating resources from underutilized fixed-route operations to flexible

TNC-based service, agencies can maintain service availability and spatial coverage while achieving meaningful cost savings.

Table 5-2: Comparison of 2 scenarios with different frequencies

Case	#Passengers	#TNCs	Bus Cost	TNC Cost	Saving
1	34	12	111.15	103.57033	7.579674
2	34	12	222.3	115.15228	107.1477

5.4. Effect of Bus Stop Density

In this section, we compare two scenarios that differ in the number of bus stops retained beyond the truncation point. The goal of this analysis is to isolate the effect of stop density, a supply-side design characteristic on TNC operating cost and the resulting system savings. As in earlier analyses, we keep the same set of passengers and retain their original OD locations to ensure that any differences in outcomes are solely attributable to changes in stop configuration rather than changes in demand. Figure 5-4 provides an illustrative example of how the two scenarios are structured.

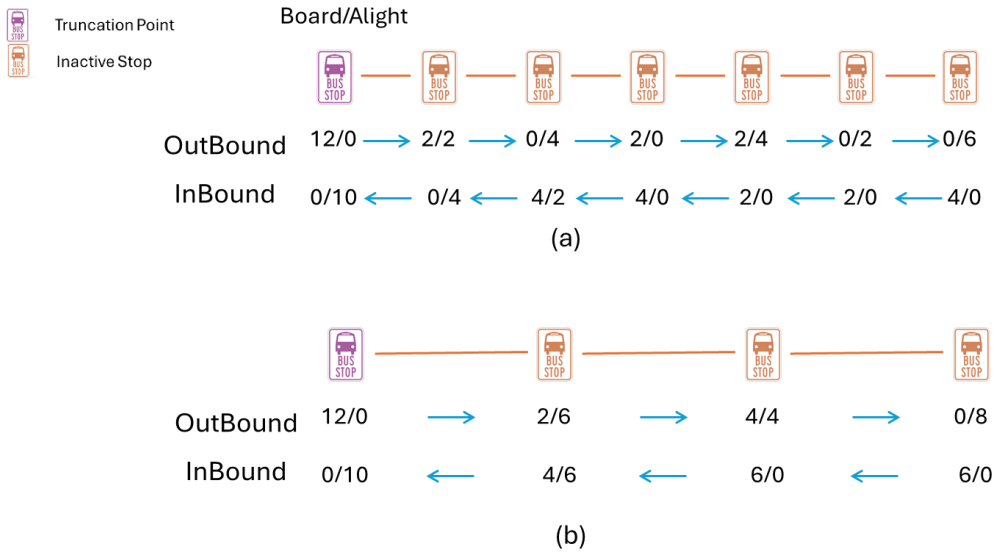


Figure 5-4: Example route with 2 different bus stop densities

In subplot (a), Case 1 represents the base scenario, where six bus stops are truncated. In subplot (b), Case 2 reduces the stop density by retaining only three of the stops while keeping the same passenger ODs. When fewer stops are available, some passengers must walk farther to access the service, and therefore, their allowable time windows are expanded to reflect this additional walking time. The number of passengers and their travel needs remain constant across both scenarios; only the original available pickup/drop-off stops change. By comparing these two setups, we can evaluate how reducing stop density, meaning consolidating passengers into fewer access points, affects ride-matching efficiency and the overall cost of substitution. This analysis provides insight into whether agencies can further increase cost savings by strategically eliminating closely spaced stops, without reducing coverage or excluding riders. Table 5-3 shows the result of the example in Figure 5-4.

In this comparison, we make one simplifying assumption: although Case 1 involves more stops and therefore may introduce additional travel time for the bus, and Case 2 may require more time at each stop due to a greater number of passengers boarding or alighting, these effects are treated as offsetting one another and are not explicitly modeled. Under this assumption, the total bus operating cost remains effectively the same in both scenarios. While the number of required TNC vehicles does not change, the total TNC cost becomes slightly lower in the lower–stop-density case. This occurs because the passengers' OD locations remain constant, but when fewer stops are available, some passengers must walk farther to reach their stop. The resulting wider time windows make it easier for the ride-matching algorithm to group riders efficiently into shared TNC trips, thereby improving pooling opportunities.

Table 5-3: Comparison of 2 scenarios with different stop densities

Case	#Passengers	#TNCs	Bus Cost	TNC Cost	Saving
1	34	12	111.15	103.57033	7.579674
2	34	12	111.15	101.14783	10.00217

This finding suggests that providing door-level service through TNC substitution is not highly sensitive to stop density, provided that demand remains unchanged. However, a notable trade-off emerges on the passenger side: although fewer stops may enable more efficient ride-matching and reduce overall system costs, passenger disutility, stemming from longer walking distances and potentially greater inconvenience, can increase substantially in less dense stop configurations. In practice, agencies must weigh cost efficiency against passenger experience as they consider how aggressively to consolidate stops in low-demand segments.

5.5. Stop-level TNC Service

In a stop-to-stop level design (similar to chapter 3), TNC vehicles directly replace fixed-route buses and do not provide first- or last-mile service. Hence, passengers must walk between their home/work locations and bus stops. The goal of this analysis is to determine whether a stop-level service, as a "reduced" version of the door-level service, could lower TNC costs further and assess the difference in passenger disutility between the two service designs.

Using Route 92 as an example, Figure 5-5 compares the costs of door-level (benchmark design) and stop-level services in the truncated segments, along with passenger disutility. In both the morning and evening scenarios, the stop-level TNC service is less

expensive than the door-level service; however, the difference is minimal. In the morning scenario, switching to a stop-level service from a door-level service reduces the average cost by only about 2%. In the evening scenario, the cost reduction is slightly greater, at around 5%. This indicates that although a benchmark door-level service requires TNC vehicles to detour for passenger pick-ups and drop-offs, a well-designed TNC route results in only a marginally higher cost or even a lower cost compared to the stop-level service. Figure 5-5 (b) and (d) illustrate the total disutility for the three services on Route 92 during morning and evening hours. In the morning scenario, both door- and stop-level TNC services improve passenger utility (i.e., reduce disutility) compared to the fixed-route bus, though the improvement with the stop-level TNC service is minor. The stop-level service reduces passenger disutility from in-vehicle time, but walking-related disutility remains the same as with the fixed-route bus service. In the evening scenario, the stop-level service for two of the candidates increases passenger disutility compared to the bus due to longer transfer time.

In some situations, especially when there are fewer passengers, door-level service can be more cost-effective than stop-level service. This occurs when the route to pick up or drop off passengers is shorter than the distance between bus stops, though this is relatively rare. In most cases, the total passenger disutility for stop-level service is higher than for door-level service, except when passengers have very short walking distances to the stops, which can offset potential delays caused by routing and stopping in door-level service. These findings indicate that while door-level service is slightly more costly than stop-level service, it significantly reduces passenger disutility. The implication for transit agencies is that, when considering a TNC substitution, offering a door-level service may be a better option than a stop-level service.

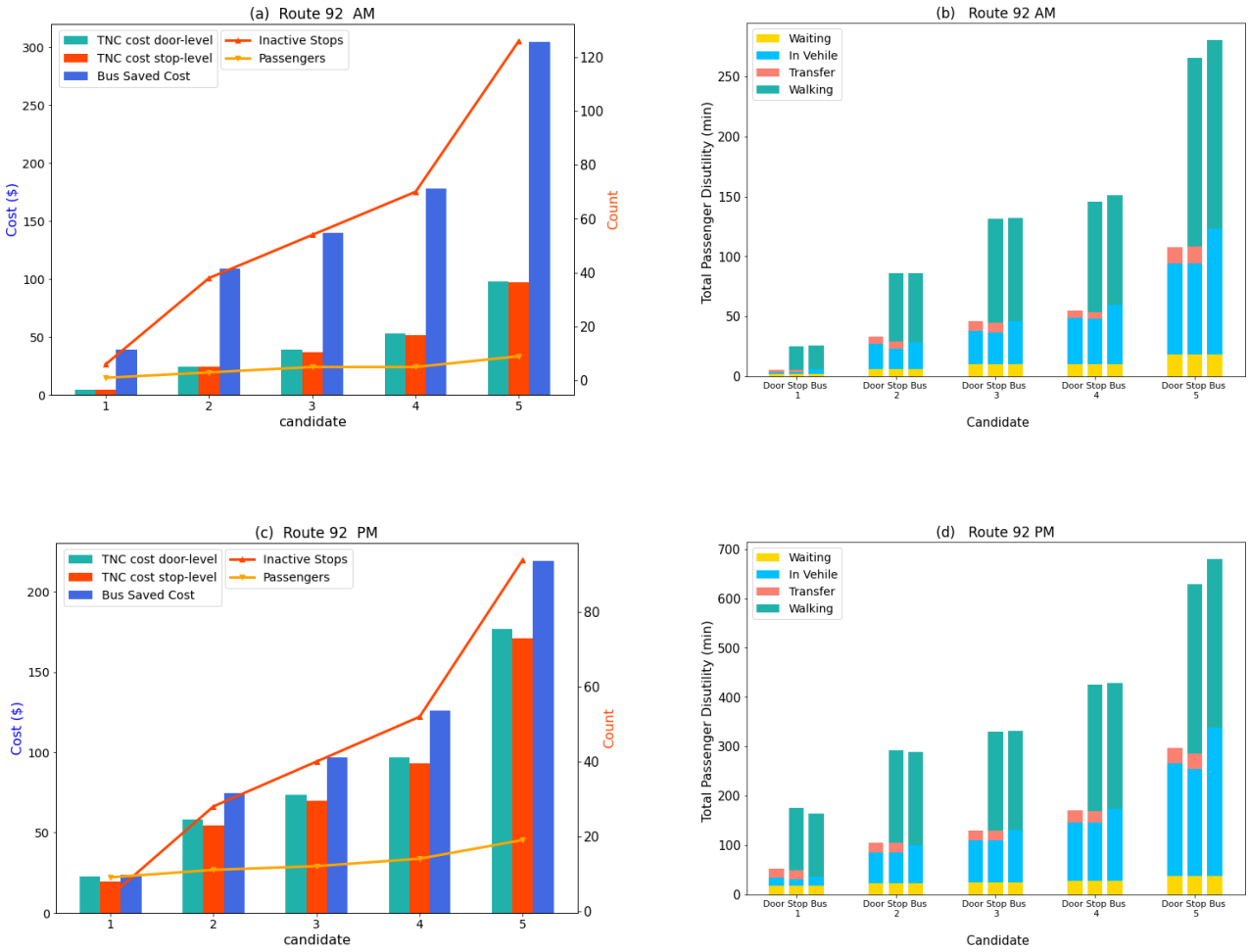


Figure 5-5: Cost and Passenger Disutility (Door-level versus Stop-level)

5.6. Non-cooperative Scenario between Transit Agencies and TNCs

Previous discussions have demonstrated the effectiveness of a transit–TNC partnership. This section addresses the question: What would the cost and passenger disutility be if there were no cooperation (contract) between a transit agency and a TNC?

In a non-cooperative scenario, passengers independently request ride-hailing services, which transport them from bus stops to their final destinations. Transit agencies fully subsidize these ride-hailing costs to compensate for the truncation of normal bus services. In this analysis, we compare the total cost to transit agencies in both the benchmark

cooperative scenario and the non-cooperative scenario. Using Route 92 as an example, Figure 5-6 compares three service designs: (1) our proposed benchmark design (transit–TNC cooperation, labeled "TNC", in green), (2) the non-cooperative scenario (labeled "NCTNC", in tan color), and (3) traditional fixed-route bus operations (in blue). Subplots (a) and (c) show cost comparisons during the morning and evening peak periods, respectively. The results reveal that across all demand levels, the non-cooperative scenario consistently incurs higher costs than the cooperative TNC operation, indicating that transit agencies would need to provide greater subsidies. In the evening peak, the cost of non-cooperative service even exceeds that of conventional fixed-route bus operations, making the TNC service economically unviable as a replacement without a formal partnership. Furthermore, as passenger numbers increase, the cost gap between contracted and uncontracted services widens.

However, as shown in subplots (b) and (d), the uncontracted service improves passenger utility, mainly due to reduced in-vehicle travel time and fewer intermediate stops. This suggests that while non-cooperative service may enhance the rider experience, the increased subsidy burden makes it financially unsustainable for transit agencies. Beyond cost savings, the cooperative model offers other, less immediately obvious advantages. With a formal partnership in place, transit agencies can coordinate TNC services with bus arrivals, assist passengers in pre-booking rides, and offer streamlined payment options. Such integration can enhance user trust, improve safety, and address privacy concerns by matching registered drivers with transit riders.

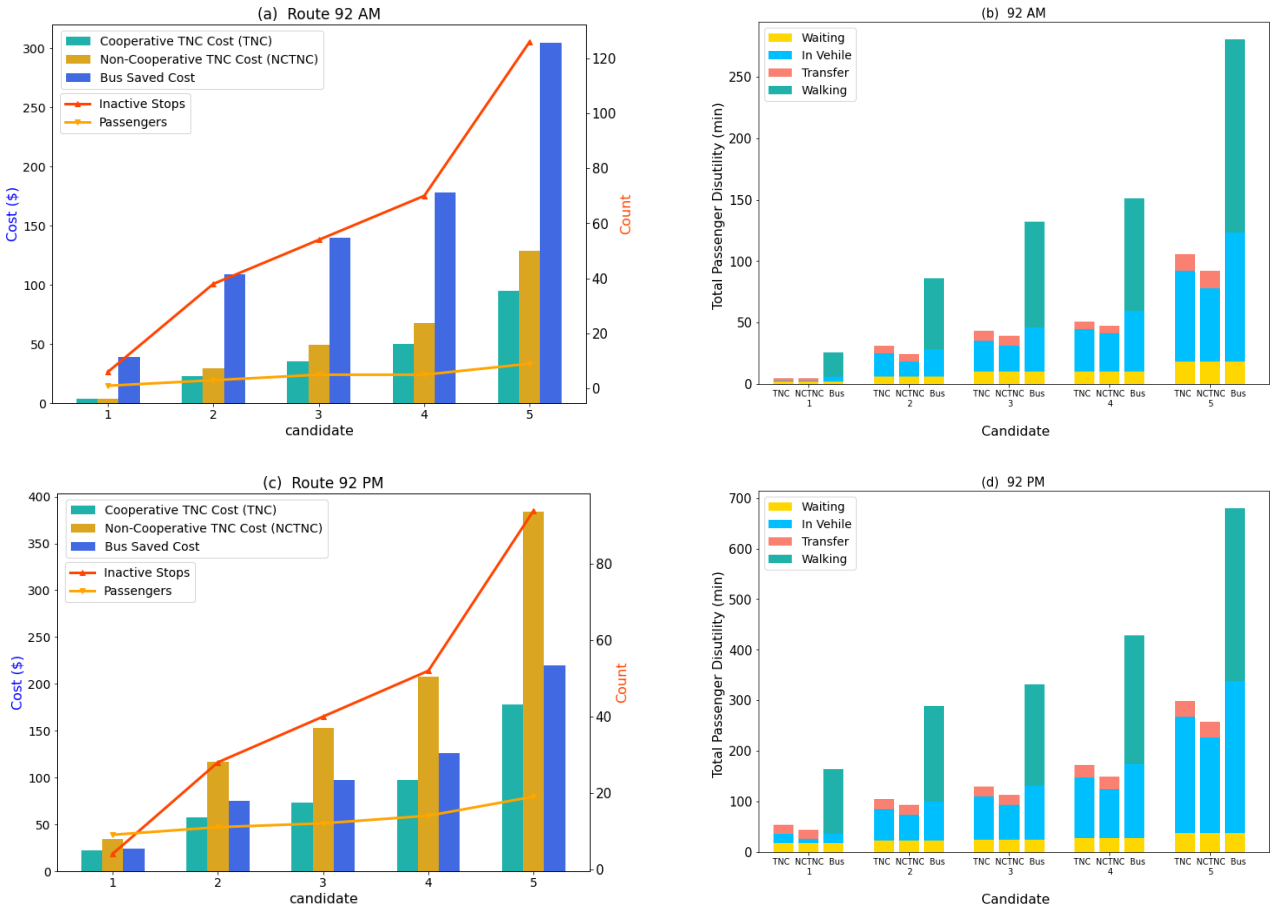


Figure 5-6: Cost and Passenger Disutility of TNCs Contracted vs Uncontracted Service

Interestingly, Figure 5-6 (a) also shows scenarios where the non-cooperative cost is higher than the cooperative scenario but still lower than the original fixed-route cost. In these cases, even if TNCs are unwilling to form a formal partnership, transit agencies could still truncate the bus service and subsidize individual ride-hailing trips. This approach can reduce overall agency costs while improving passenger utility, as illustrated in Figure 5-6 (b). Conversely, in cases like those shown in subplot (c), where non-cooperative costs exceed bus operation costs, maintaining conventional fixed-route services remains the more cost-effective choice.

There is also a variation of the non-cooperative scenario where transit agencies offer no subsidy at all for ride-hailing services. While this could improve agency finances by eliminating the cost of servicing truncated segments, it may have several negative implications. First, it introduces equity concerns, particularly for low-income workers who rely on these transit services for their daily commutes. Second, higher out-of-pocket costs may reduce the system's attractiveness, leading to a decline in ridership. Third, passengers may fully switch to TNCs, creating direct competition and potentially reducing ridership even on high-performing fixed-route segments.

5.7. Demand Responsive Transit (DRT) versus TNC as a Substitution

Besides TNCs, in-house Demand-Responsive Transit (DRT) service could be another alternative to substitute fixed-route transit in low-demand areas. This subsection compares the service design of DRT versus TNC as a means of providing door-level service. To evaluate DRT service in low-demand areas, we assume the use of *Ford Transit* vehicles: each vehicle carries up to 14 passengers, is available throughout the study period, and has an ownership cost of $0.28 per mile (based on a $56,400 purchase price and a 200,000-mile lifespan) (Ford Motor Company, 2025). In addition, maintenance and fuel expenses are estimated at $1.11 per mile (U.S. Department of Energy, 2025), and drivers are paid a minimum of $16 per hour.

Figure 5-7 compares the cost and passenger disutility of TNC, DRT, and conventional bus services on Route 92 during morning and evening periods. In 9 out of the 10 candidate scenarios in subplots (a) and (c), DRT incurs higher operating costs than TNC when ridership is low, except for Candidate 5 in the evening period (subplot c), which features the highest ridership among all scenarios. In most candidates (excluding Candidates 1, 2, and 3 in the evening), both TNC and DRT services are more cost-effective than conventional buses. This

suggests that both modes are viable substitutes for fixed-route services in low-demand areas. However, when demand remains low, TNCs are more cost-efficient; when demand is relatively high within these low-demand zones, DRT becomes the preferred option.

In the first three candidates of subplot (c), where the average number of inactive stops per passenger is low, DRT costs even exceed those of buses. This occurs because DRT provides full door-level service, while buses offer stop-level service and operate over shorter, truncated segments, resulting in lower operating costs for fixed-route services. For example, in Candidate 1 during the evening, the truncated segments are so short that additional shuttles are needed to meet passenger time constraints and connect to transfer points efficiently. In contrast, longer segments in other candidates allow shuttles more time to consolidate ride requests, reducing the number of required vehicles.

Subplots (b) and (d) of Figure 5-7 show that total passenger disutility for DRT is generally higher than, or occasionally comparable to, that of TNCs. In low-ridership scenarios—such as the morning period or Candidate 1 in the evening—each DRT shuttle typically carries fewer than three passengers, similar to a TNC vehicle. As a result, the number of DRT vehicles deployed approximates the number of TNC vehicles, yielding comparable levels of in-vehicle travel time and, therefore, similar disutility.

Candidate 5 in the evening shows a different trend. While operating costs are lower due to higher passenger volumes, the disutility is also significantly reduced, lower than that of conventional buses and only slightly higher than that of TNCs. This suggests that DRT is a competitive alternative in relatively higher-demand scenarios. Therefore, if current operating costs and driver wages are acceptable to unions and transit agencies, implementing DRT services in such cases—particularly in compact service areas with

concentrated demand—could be advantageous. However, in cases of low or dispersed demand, DRT may face underutilization and idle vehicle issues, similar to those seen in conventional fixed-route systems.

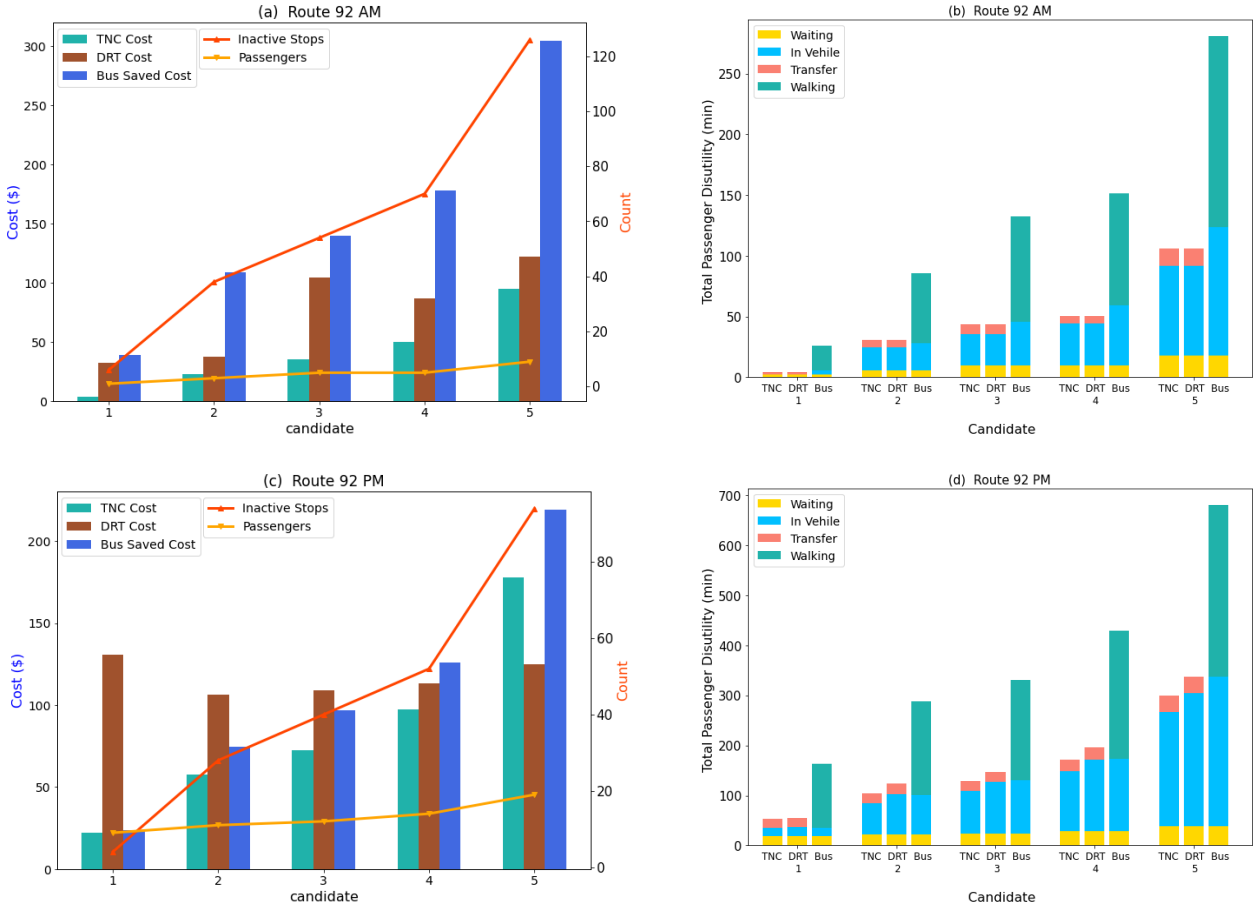


Figure 5-7: Cost and Passenger Disutility under Different Services

In summary, although DRT offers a flexible alternative to traditional bus services, its larger vehicle size, higher ownership cost, and fixed labor expenses make it less suitable than TNCs for segments with limited ridership. However, if demand in truncated segments increases, or if the main objective is to improve first-mile/last-mile connectivity, deploying DRT shuttles can be a viable and effective strategy.

CHAPTER 6: Analysis of Influencing Factors

Another objective of this study is to examine how certain factors, specifically, the characteristics of the transit network and travel demand, affect the effectiveness of TNC substitution. The key factors considered are summarized in Table 6-1. The analysis is based on 90 data points from the Long Beach network during off-peak periods, including early morning (AM) and evening (PM). The data encompass five potential truncation points across nine selected routes, capturing both route characteristics and operational parameters, as well as the associated TNC operating costs and total savings. Total savings are calculated as the difference between the cost reductions achieved by truncating fixed-route bus operations and the corresponding TNC operating costs, providing a quantitative measure of the economic feasibility of the proposed substitution.

Table 6-1: Key Factors/Metrics in a Truncated Segment

Metric	Definition
The no. of inactive stops	Count of inactive stops in truncated segments for all TNC-substituted bus trips.
Total no. of passengers	Total number of passengers for all substituted bus trips.
The no. of inactive stops per mile	Total number of inactive stops divided by total truncated miles.
The no. of passengers per bus mile	Total number of passengers divided by total truncated miles.
The no. of passengers per stop	Total number of passengers divided by the number of truncated stops.
The maximum load of buses	The maximum in-bus rider count before TNC substitution
The average load of buses	Summation of in-bus rider counts after each stop divided by the number of stops.
Total passenger miles	Summation of the multiplication of the number of passengers by the distance each passenger travels.

The first step of the analysis is to develop an equation that can guide decision-making regarding the feasibility and potential effectiveness of route truncation combined with TNC substitution for individual routes in any study area. This begins with an examination of linear relationships through multiple regression analyses, considering different combinations of the selected factors, which were mentioned in Table 6-1. These linear regressions help identify which factors most strongly influence total savings and allow for preliminary predictions about the outcomes of various truncation scenarios. Following this, a non-linear regression model is developed to more accurately capture the complex relationships between these factors and total savings, accounting for potential interactions and non-linearities that are not reflected in linear models.

In addition to regression analysis, the study investigates the correlations among all proposed factors to identify potential multicollinearity or interdependencies that could affect model interpretation. A comprehensive bivariate analysis is then conducted between the total savings and each factor, providing insights into which network or demand characteristics most strongly influence the efficiency and cost-effectiveness of TNC substitution. This approach, combining regression modeling with correlation and bivariate analysis, enables a nuanced understanding of both individual and combined effects of the factors on operational outcomes. By exploring these statistical relationships, this study contributes to the broader literature on transit cost optimization and service substitution strategies (R. L. Bertini & El-Geneidy, 2003), highlighting practical guidelines for transit agencies seeking to integrate TNC services into existing networks.

6.1. Regression

To identify a linear equation capable of predicting total savings, we estimated 92 regression models using the eight explanatory factors outlined in Table 6-1. These models included specifications with each factor individually, as well as all possible two-factor and three-factor combinations. This approach ensured that we could capture not only the isolated effect of each variable but also potential interactions between factors that might jointly influence total savings. This systematic approach allowed us to explore a broad range of potential linear relationships between the independent variables and total savings.

Among the 92 regressions, a substantial proportion produced low R-squared values, suggesting a poor overall fit and limited explanatory power. For the models with relatively strong R-squared values, we applied two additional screening criteria. First, we excluded models in which the estimated coefficients contradicted theoretical expectations, for instance, specifications suggesting that an increase in passengers per mile would lead to greater savings. Second, we eliminated models in which one or more variables had high p-values, indicating a lack of statistical significance.

After applying these filters, we retained only the models with both acceptable coefficient signs and statistically significant variables. This refinement process ensured that the remaining models were both theoretically consistent and empirically robust. Table 6-2 presents the subset of top-performing regression models, ranked according to R-squared values while satisfying these theoretical and statistical requirements. These models provide a more reliable basis for evaluating the influence of network and demand characteristics on the potential savings from TNC substitution.

Table 6-2: Summary of top regression models to predict total saving

Reg.	R^2	Passengers		Inactive stops		Passenger mile		Passengers per stop		Passengers per mile		Stop per mile	
		Coeff	P_value	Coeff	P_value	Coeff	P_value	Coeff	P_value	Coeff	P_value	Coeff	P_value
1	0.73	-2.55	0.00	1.73	0.00	-0.45	0.01						
2	0.71	-2.91	0.00	1.58	0.00								
3	0.59	-0.81	0.00							-32.12	0.00	33.22	0.00
4	0.54	-1.01	0.00					-40.07	0.12			26.32	0.00
5	0.54					-0.37	0.00	-44.91	0.00			35.65	0.00
6	0.40			1.31	0.00	-1.54	0.00						

As shown in Table 6-2, the regression results demonstrate that predicting total savings with sufficient accuracy and thereby determining whether a particular truncation and substitution strategy is financially viable cannot be fully achieved using linear models. While linear regressions provide initial insights into factor relationships, their limited explanatory power and inability to capture complex interactions make them insufficient for reliable decision-making. Consequently, this study extends the analysis by developing a non-linear specification designed to better reflect the underlying dynamics of the system. Equation 200 presents the resulting non-linear model, formulated as a six-term polynomial of degree two. This specification provides a substantially improved fit to the observed data, achieving an R^2 value of 0.95. The high explanatory power indicates that the non-linear model captures critical factor interactions and curvature effects overlooked by linear approaches, making it a more robust tool for assessing the financial feasibility of route truncation and TNC substitution strategies.

$$Saving = 237.15 \times Passenger\ per\ stop - 55.71 \times Passenger\ per\ stop\ ^\wedge\ 2$$
$$- 4.92 \times Passenger\ per\ mile + 13.62 \times Average\ load - 9.57 \times Average\ load\ ^\wedge\ 2$$
$$- 3.41 \times Passengers \quad (6\text{-}1)$$

6.2. Correlation

To evaluate potential multicollinearity among the proposed factors, pairwise correlations were calculated for all independent variables considered in the regression models. The results, presented in Figure 6-1, highlight several expected relationships. Specifically, the number of passengers exhibits a strong correlation with both the number of inactive stops and passenger mileage, reflecting the natural interdependence of these measures. Passenger counts also show moderate correlation with average and maximum bus load, further confirming their shared dependence on ridership levels. Similarly, passenger density metrics, measured as passengers per mile and passengers per stop, are highly correlated, which is consistent with expectations given their similar formulation.

The presence of these strong correlations raises concerns about the independence of variables within certain regression models. For example, the high correlation between passengers and inactive stops suggests that Regressions 1 and 2 may not adequately represent linear and independent relationships. A similar issue arises in Regression 6, where the correlation between inactive stops and passenger mileage calls into question the reliability of its results. By contrast, Regressions 3, 4, and 5 incorporate variables with lower interdependencies, thereby providing more statistically robust specifications.

Even within the non-linear framework of (6-1), some degree of dependency remains, particularly between passengers per mile and passengers per stop. This finding underscores

a broader limitation: a single regression model may not be capable of fully capturing the multidimensional and interrelated nature of the factors influencing savings from truncation and TNC substitution. Nevertheless, in order to provide transit agencies with practical guidance, this study proceeds by examining the individual relationships of each factor with TNC cost, bus cost savings, and total savings.

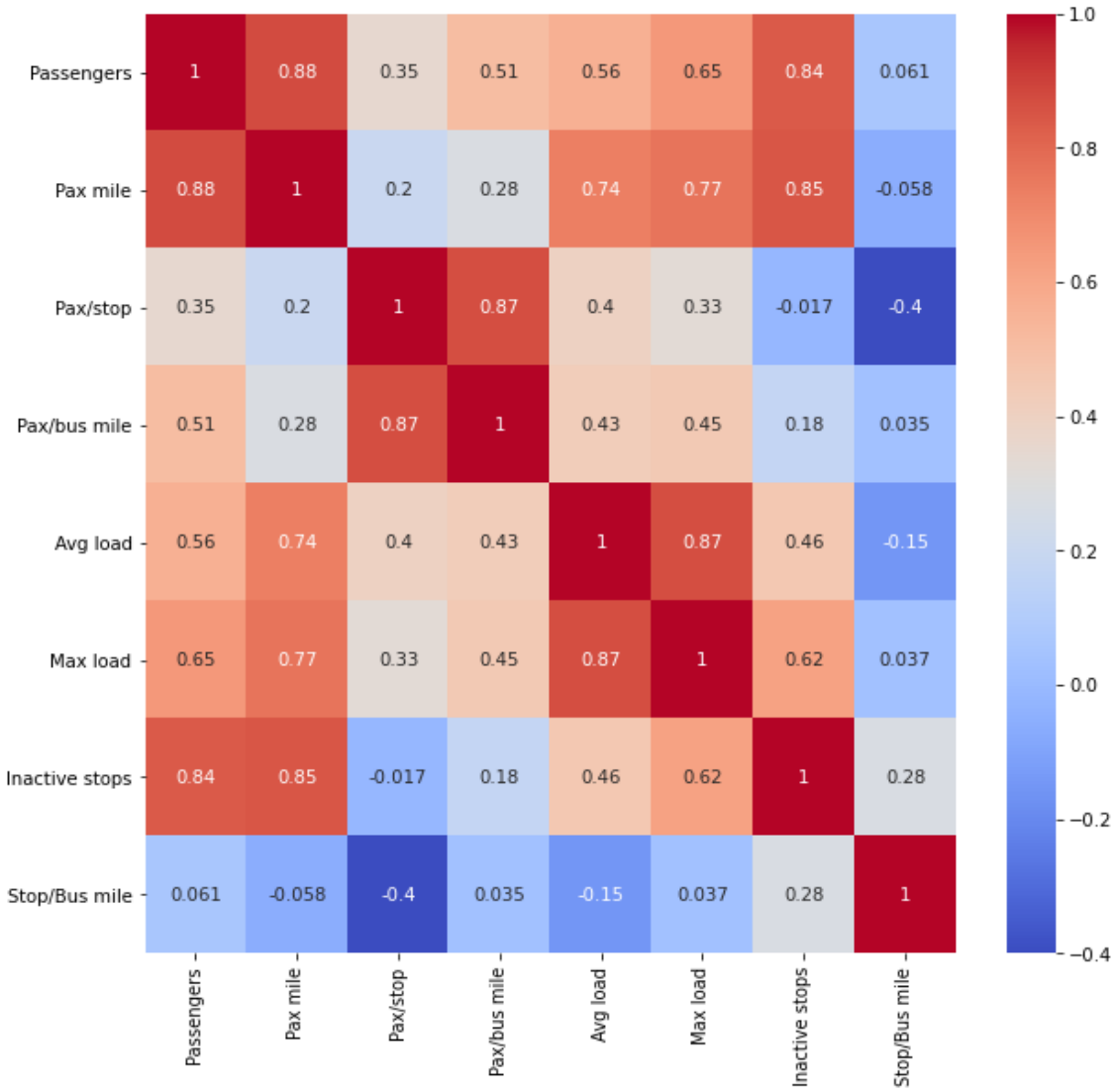
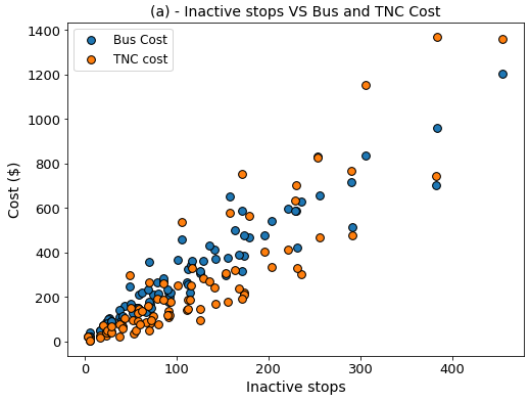


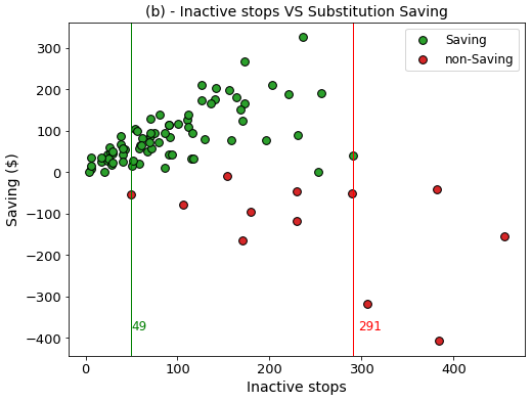
Figure 6-1: Heatmap of correlations across all factors

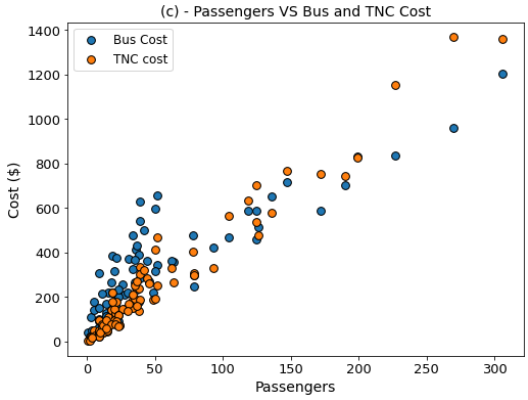
6.3. Bivariate Analysis

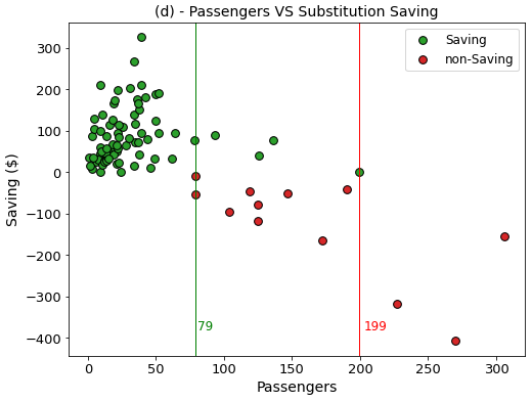
Figure 6-2 illustrates the trends between savings and different metrics. Each dot represents a data point corresponding to the savings at a potential truncation location. In each subplot on the left, we compare the trend of fixed route bus costs for the truncated segment (potential savings once substituted by TNCs) against total TNC costs, in relation to each metric. The subplots on the right show whether overall cost savings could be achieved with the selected truncation point. Green dots indicate positive overall savings, while red dots represent "non-saving" truncation points where TNC substitution would result in a cost increase.

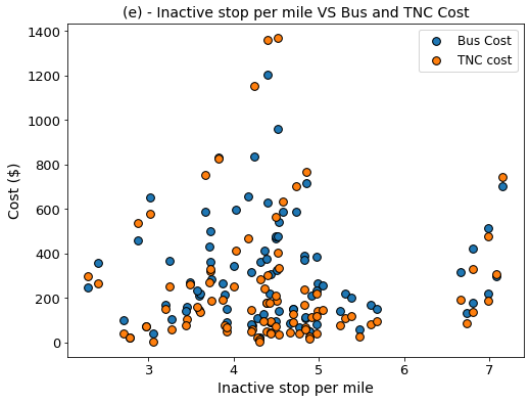
In the subplots on the left, we observe a positive correlation between TNC cost and several metrics, including inactive stops (a), total number of passengers (c), maximum load (k), average load (m), and passenger miles (o). Similar positive correlations are observed between bus cost and these metrics. A roughly linear positive relationship exists between TNC/bus costs and inactive stops (a), total number of passengers (c), and passenger miles (o). In subplots (a), (c), (k), (m), and (o), we notice that bus costs start higher, but TNC costs increase at a faster rate, eventually surpassing bus costs. This suggests that for smaller values of inactive stops, passenger numbers, and bus loads, TNCs are more cost-efficient than fixed-route buses. The number of passengers per mile (g) and per stop (i) do not show a clear correlation between costs and metrics, but both reveal a trend of high bus costs initially, followed by high TNC costs later. This provides evidence supporting the viability of replacing fixed-route buses with TNCs in low-demand scenarios.

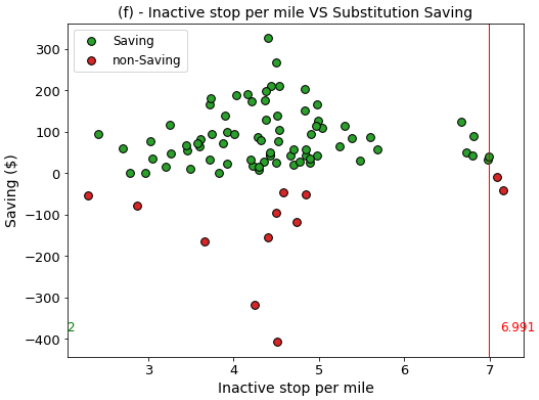

(a) - Inactive stops VS Bus and TNC Cost
Bus Cost
TNC cost
Cost ($)
Inactive stops

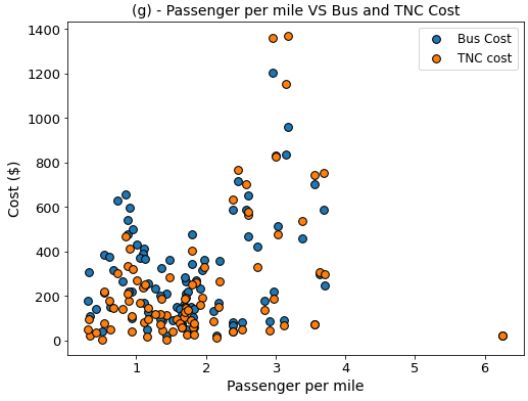

(b) - Inactive stops VS Substitution Saving
Saving
non-Saving
Saving ($)
49
291
Inactive stops

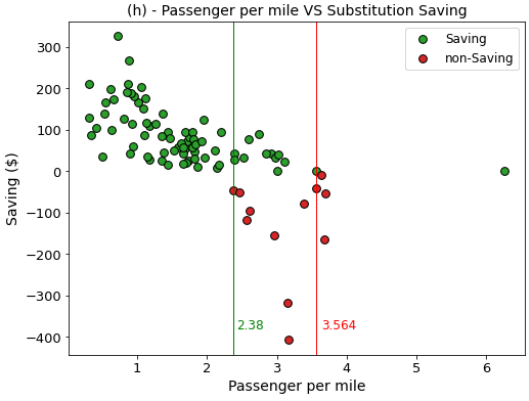

(c) - Passengers VS Bus and TNC Cost
Bus Cost
TNC cost
Cost ($)
Passengers


(d) - Passengers VS Substitution Saving
Saving
non-Saving
Saving ($)
79
199
Passengers


(e) - Inactive stop per mile VS Bus and TNC Cost
Bus Cost
TNC cost
Cost ($)
Inactive stop per mile


(f) - Inactive stop per mile VS Substitution Saving
Saving
non-Saving
Saving ($)
2
6.991
Inactive stop per mile


(g) - Passenger per mile VS Bus and TNC Cost
Bus Cost
TNC cost
Cost ($)
Passenger per mile


(h) - Passenger per mile VS Substitution Saving
Saving
non-Saving
Saving ($)
2.38
3.564
Passenger per mile

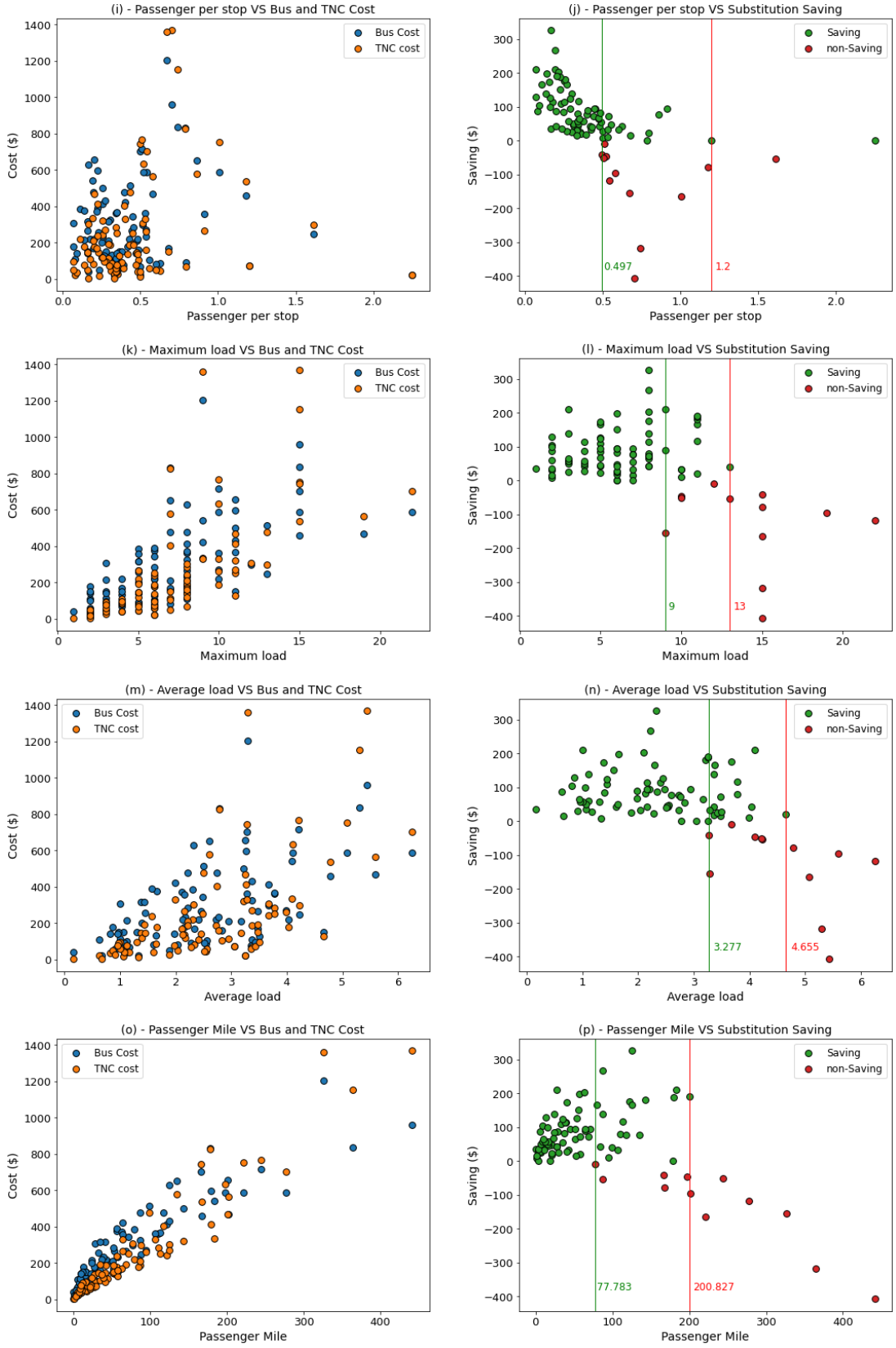


Figure 6-2: Bus, TNC cost and Total Savings versus Multiple Factors

To better quantify the level of "low demand" necessary for cost-saving TNC substitution, we compare the saving and non-saving cases in the right column of the figure. In these subplots we can draw two boundaries. The left green boundary shows that before reaching that threshold, we only observe the saving and therefore, the substitution is efficient. On the other hand, the red boundary shows the threshold beyond which, we do not observe any savings, which indicates that conventional buses are better options. For instance, in subplot (b), the boundaries suggest that TNC substitution should not be considered if a truncated segment has a total of 291 stops for all removed bus trips during the off-peak period, but it probably can be beneficial when the number of stops is less than 49. Similar interpretations apply to other metrics, with several important takeaways. The number of passengers per stop (j), maximum load (l), and average load (n) reflect the influence of bus ridership on the feasibility of TNC substitution, particularly the number of passengers per stop. This metric indicates that TNC substitution is highly likely to be cost-effective when the average number of riders per stop in the truncated segment is below 1.2.

In addition to these boundaries, we observe clusters of "all-green" dots in the top-left corner of most subplots. These are "safe zones" where TNC substitution consistently yields cost savings. These subplots suggest that replacing fixed-route buses with TNCs would most likely help LBT save costs within these ranges of metrics. However, decisions on TNC substitution should not be based on a single metric; comparing multiple metrics significantly improves the quality of decision-making.

CHAPTER 7: Real-world Cases, Takeaways, Challenges and Benefits

Building on the quantitative analyses of financial feasibility and system performance presented in the previous chapter, this chapter shifts the focus to real-world applications of TNC partnerships in public transit. While the prior analysis highlighted the conditions under which truncation and substitution strategies may yield cost savings and operational benefits, the practical implementation of such services depends on institutional, contractual, and user-oriented factors that extend beyond the scope of purely numerical models.

To explore these dimensions, we begin by reviewing examples of existing and past partnerships between transit agencies and TNCs, highlighting the diverse service designs, fare structures, and contractual arrangements that have emerged. These examples serve not only to illustrate the breadth of operational models, but also to show how local context, funding availability, and policy priorities shape the outcomes of such collaborations. Following this overview, we focus more closely on three representative operations selected for in-depth examination. This qualitative perspective provides valuable insights into the motivations behind such partnerships. The chapter then turns to a broader discussion of the practical challenges that transit agencies and practitioners may encounter when considering TNC partnerships. To address these concerns, we highlight how careful planning and detailed contractual design can mitigate risks and improve decision-making. Finally, we summarize the potential benefits of TNC collaborations for both agencies and riders, such as cost savings, improved connectivity, and enhanced service flexibility.

7.1. Real-world Partnership Example

Public transit agencies across the United States are increasingly leveraging partnerships with TNCs and private mobility providers to enhance the flexibility and responsiveness of their systems. While the motivations and structures of these collaborations vary, they share a common strategic goal: improving access to transit while preserving the public sector agencies' equity and service obligations. These initiatives demonstrate a significant shift from viewing TNCs as competitors to incorporating them as service delivery partners under a defined contractual and performance framework. We conducted a comprehensive review of the literature on partnerships that transit agencies have formed with TNCs in the United States. Table 7-1 provides a categorized summary of ten programs that exemplify these partnership models.

Table 7-1: Examples of recent partnerships of transit agencies and TNCs

Program / Service	City / Agency	Existing or Pilot Year	Partner / Provider	Service Purpose / Type	Target users / Area	Fare / Subsidy
RTA Connect On-Demand	Greater Dayton RTA (Dayton, OH)	Existing	Lyft, Uber, RTA call-center, local lift providers	On-demand door-to-door within defined zones	General public within zones; connects to transit centers	Fare of $3.00 per trip
SANDAG Flexible Fleets / Guaranteed Ride Home	San Diego Association of Governments	2022 (planning & contracts started)	Via (microtransit), Circuit Transit (NEV), others	Flexible fleets, microtransit, emergency ride reimbursement	Jurisdictions across San Diego County; commuters for emergency purposes	Guaranteed Ride Home reimbursement up to $100 per ride three times per year
Solano Mobility (Suisun/ Benicia/Vallejo/ Capitol Corridor)	Solano County, CA / Solano Transportation Authority (STA)	2019-2023 (multiple programs) Existing	Lyft (primary); local taxis for some programs	Subsidized local Lyft rides; first/last mile; taxi programs; commuter incentives	Residents, seniors, ADA, low-income, commuters in Solano County	Suisun $2 one-way (low-income $1.50 up to $20); Benicia $4 (qualified) up to $20; First/Last Mile 60% off up to $20 (80% low-income)
MBTA The RIDE Flex	MBTA (Boston, MA)	Evolved from pilots; Existing	Uber, Lyft (Flex providers), TRAC scheduling	On-demand supplement to ADA paratransit (The RIDE)	ADA / RIDE-certified customers in MBTA area	$3 co-pay; MBTA subsidizes up to $40 per trip; rider pays amount over $43 total

Program / Service	City / Agency	Existing or Pilot Year	Partner / Provider	Service Purpose / Type	Target users / Area	Fare / Subsidy
Summit Uber Commuter Pilot	City of Summit, NJ	Oct 3, 2016 - Mar 31, 2017 (pilot)	UberX	Door-to-station commuter rides to/from train station	Summit residents (initially 100 participants)	Fare equivalent to daily parking fee (pilot participants)
TriMet RideTap / moovel integration	TriMet (Portland, OR)	Mid-2010s (pilot)	moovel (RideTap SDK), integrates Lyft/Car2Go	App integration for multi-modal trip planning	Smartphone-owning TriMet riders	N/A (integration; no subsidy)
TAM GETSMART 17	Transportation Authority of Marin (TAM), Marin County, CA	2017 (pilot)	Lyft Line	Discounted Lyft Line to/from SMART stations (first/last mile)	Commuters to/from SMART stations in Marin County	Up to $5 off via promo code GETSMART17 after $2 initial fare
Marin County Emergency Ride Home (ERH)	Marin County, CA	Existing	Taxi, Uber, Lyft or equivalent (reimbursed)	Emergency ride reimbursement for commuters using alternative commutes	Workers/students in Marin County who use non-SOV commuting	Reimbursement up to $125 per trip; up to 4 trips per year
RTD Access-on-Demand	RTD (Denver, CO)	Existing	Uber, Lyft, Metro Taxi, zTrip	Subsidized curb-to-curb service for Access-a-Ride certified customers	Access-a-Ride certified customers within RTD service area	RTD subsidizes first $25 of each trip; customer pays excess; policy limits (60 trips/month etc.)
WMATA — Abilities-Ride	Washington Metropolitan Area Transit Authority (DC region)	2017 (pilot) Existing	TNCs referenced as providers of Abilities-Ride	Alternative to MetroAccess — on-demand taxi/sedan service for eligible riders	MetroAccess-eligible customers within WMATA service area	Rider pays first $5, Metro pays next $15, any amount over $20 billed to customer

The program details in Table 7-1 were obtained from agency webpages, strategic reports, public press releases, and pilot program documents, including but not limited to:

- RTA Connect On-Demand: (Greater Dayton RTA, 2025), (Miami Valley Ride Finder, 2025), (Bryan Ripple, 2018)
- SANDAG Flexible Fleets / Guaranteed Ride Home: (SANDAG, 2025)
- Solano Mobility (Suisun/ Benicia/Vallejo/ Capitol Corridor): (Solano Transportation Authority, 2022), (STA, 2019), (Solano Mobility, 2025)

- MBTA The RIDE Flex: (MBTA, 2025), (Uber Transit, 2019), (Mass, 2021)
- Summit Uber Commuter Pilot:(City of Summit, 2016), (Uber, 2016)
- TriMet RideTap/ moovel integration: (Mass Transit, 2016), (Jen Kinney, 2016), (Michael Andersen, 2016)
- TAM GETSMART17 (Lyft Line to SMART): (TAM, 2017)
- Marin County Emergency Ride Home (ERH): (Marin Commutes, 2017)
- RTD Access-on-Demand: (RTD, 2025)
- WMATA/ Abilities-Ride: (WMATA, 2025)

One of the most common applications of these partnerships is improving first- and last-mile connectivity. Programs such as TAM's GETSMART17 in Marin County, CA, the Summit, NJ Uber Commuter Pilot, and Solano Mobility offer subsidized Lyft or Uber trips to regional rail. TAM provided discounted Lyft Line rides to SMART stations, Summit matched Uber fares to parking fees, and Solano Mobility offered reduced-fare Lyft trips supporting Capitol Corridor access. These efforts avoid costly parking expansion and make regional rail more accessible to residents living beyond walking distance.

A second category focuses on expanding coverage in low-density areas where fixed routes are costly to operate. Dayton, OH RTA Connect On-Demand and SANDAG, CA's Flexible Fleets use zone-based, curb-to-curb services operating through TNCs and agency call centers. Riders request trips within defined zones or to transit centers at a flat cost, allowing agencies to maintain coverage without running underutilized buses while retaining control over fares, branding, and service areas.

The goal of this study aligns with these coverage-oriented partnerships but differs in approach. Rather than expanding reach, this dissertation optimizes fixed-route networks by

identifying and removing unproductive segments. No formal framework currently guides TNC substitution; this research introduces one, incorporating real-world constraints and evaluating impacts on agencies, riders, and drivers. It also recommends reallocating buses and resources after removing inefficient segments.

Some partnerships aim to improve paratransit and accessibility. Boston, MA's MBTA RIDE Flex, Denver, CO's RTD Access-on-Demand, and WMATA Abilities-Ride in Washington, DC region offer ADA-eligible riders same-day trips via Uber, Lyft, or taxi with fare caps. These programs reduce operational burdens, improve rider independence, and maintain compliance with ADA requirements.

A final category centers on digital integration rather than trip provision. TriMet's RideTap/Moovel platform integrates TNC and car-share options into trip planning, positioning the agency as a mobility manager coordinating multiple providers within a unified app.

Taken together, these efforts show a shift from isolated pilots to strategic mobility management. Agencies use TNCs not to replace public transit, but to fill service gaps, enhance accessibility, and reduce costs while keeping transit as the regional mobility backbone.

7.2. Transit Agency Interviews and Insights

Building on the overview of some of TNC–transit partnerships in the US, this section presents the insights we collected by conducting interviews with three agencies that have implemented some of the most mature and distinctive collaborations: Dallas Area Rapid Transit (DART), LA Metro, and the Pinellas Suncoast Transit Authority (PSTA). We reached out to over 20 transit agencies in multiple regions that report on their websites that they maintain partnerships with TNCs. Among them, only three agencies responded and agreed

to participate in an interview with us. The information in this section is derived from structured interviews conducted with representatives from these agencies, designed to capture detailed insights into the decision-making processes and implementation strategies. The list of interview questions discussed during these sessions is provided in the Appendix for reference and methodological transparency. The findings from these interviews demonstrate how public agencies are operationalizing the concept of "mobility as a service" within distinct regional, social, and financial contexts.

1. Dallas Area Rapid Transit (DART): Integrating Microtransit and TNC

DART manages one of the most extensive multimodal transit systems in the United States, serving more than 700 square miles through rail, bus, paratransit, and on-demand modes. Its GoLink program, covering over thirty service zones, has become central to DART's strategy for reaching low-density and suburban areas that fixed routes cannot efficiently serve. Introduced in 2017 through the FTA's Mobility on Demand Sandbox program, GoLink offers shared, curb-to-curb rides bookable by app or phone. A $3 fare includes up to three hours of access to both GoLink and DART's fixed routes, and a $6 day pass provides full network coverage. Crucially, the system merges DART's own vehicles with rides provided through Uber and, beginning in 2025, Lyft, with dispatching managed through Spare Labs' technology (Spare Labs Inc, 2025). This hybrid "mixed supply" approach allows demand-based allocation: DART vehicles handle predictable activity while TNCs absorb surges or remote trips. Uber currently fulfills about 70 percent of GoLink rides.

The model delivers strong results. Average weekday ridership ranges between 6,000 and 7,000 with productivity near 4.7 passengers per vehicle hour, which is high for a zone-based service. Average trip length is four miles, with about a 12-minute wait time. After

DART's 2022 bus network redesign, which replaced low-performing routes with microtransit zones, the agency recorded substantial ridership growth. Roughly 70 percent of trips serve local needs such as shopping or appointments, while 30 percent connect to bus or rail stops, showing that GoLink functions as both a coverage and feeder service.

DART maintains detailed performance monitoring to balance cost and service quality. The average cost per passenger is about $15.61, less than half that of the former fixed-route alternatives. Uber trips average under $10 per rider, while dedicated fleet operations cost around $30 per hour. To sustain efficiency, DART has introduced trip caps, clustered pickup points, and expanded its contractor pool. Rider satisfaction remains high, averaging 4.9 out of 5, largely due to reliability and curb-to-curb convenience. Although certain zones still underperform, GoLink has become a fully integrated component of DART's multimodal network rather than a peripheral pilot.

2. LA Metro: Broadening Access through the Mobility Wallet

While DART focuses on operations, LA Metro's Mobility Wallet addresses financial access as a subtler but equally important barrier to shared mobility participation. Many Los Angeles residents, especially those in lower-income households, lack the traditional banking tools needed to use app-based services. The Mobility Wallet overcomes this by providing eligible participants with $1,800 per year on a prepaid debit card that can be used for transit, bikeshare, carshare, taxis, and TNCs like Uber and Lyft. The funds, distributed via U.S. Bank, are coded to transportation-specific merchant categories to prevent non-eligible purchases. This design enables mobility equity without building new operations. Early results show that around half of recorded transactions are TNC trips, typically short local journeys for errands, appointments, or family visits. The average cost per trip, which is about $19 to $20, is

comparable to Metro's own per-trip bus expenditure, suggesting that the wallet provides cost-neutral flexibility while improving convenience for participants.

The program also yields valuable behavioral data. In its next phase, Uber promo codes will allow Metro to capture anonymized trip details, providing insight into how financial subsidies reshape travel patterns. Although the Mobility Wallet does not involve direct contracting with TNCs, it represents a new form of collaboration, financial and data integration, that broadens the reach of public support into privately operated modes. In doing so, LA Metro redefines what partnership can mean: not outsourcing service but ensuring that all residents can access the expanding landscape of shared mobility.

3. Pinellas Suncoast Transit Authority (PSTA): Layered Mobility through TNC Integration

PSTA demonstrates how multiple TNC collaborations can coexist within one agency to serve different user groups. Its portfolio includes Direct Connect, TD Late Shift, and Mobility on Demand, each addressing a distinct gap in service coverage.

Direct Connect began in 2016 to preserve mobility after bus route reductions following a failed tax referendum. Riders traveling to or from designated transit hubs receive a $5 subsidy per trip ($25 for wheelchair-accessible rides) using Uber, Lyft, or taxis between 5 a.m. and midnight. The service is open to all riders and operates entirely within standard TNC apps, functioning primarily as a first- and last-mile solution but also serving local, short-distance trips.

The TD Late Shift program extends access for low-income workers during overnight hours when fixed-route service is unavailable. For $20 per month (including a regular bus pass), participants can take up to 25 subsidized rides between 10 p.m. and 6 a.m. Eligibility

is limited to individuals earning below 200 percent of the federal poverty level without personal vehicles. The program has been particularly effective for service and hospitality workers whose shifts fall outside standard transit schedules.

Complementing these, Mobility on Demand offers same-day paratransit trips through Uber, Lyft, and UZURV for ADA-eligible riders. Passengers pay $4.50 for the first 20 miles plus $1 per additional mile, with up to 30 trips allowed monthly. The program now accounts for roughly two-thirds of all paratransit rides in PSTA's system, illustrating substantial adoption. Riders value its flexibility and shorter wait times compared with traditional paratransit booking.

PSTA's approach demonstrates the strength of differentiated program design, tailoring similar TNC mechanisms to multiple policy objectives. Together, its programs maintain geographic coverage, ensure access to late-night employment, and modernize paratransit operations. Recent technological integrations, including linking Direct Connect to the Transit App and introducing (814 On-Demand) microtransit and an airport shuttle, show how lessons from early pilots continue to shape wider system redesigns.

4. Comparative Reflections

Despite their differing contexts, these three agencies reveal converging principles. DART's GoLink exemplifies operational integration of TNCs into public service delivery; LA Metro's Mobility Wallet advances financial inclusion and equitable access; and PSTA's layered initiatives showcase policy adaptability across multiple user segments. All emphasize continuous iteration, refining fare policies, eligibility criteria, and data systems to balance efficiency and public accountability.

A key distinction lies in how each agency manages control versus flexibility. DART's proprietary app and mixed-fleet dispatching allow direct oversight of performance, while PSTA and LA Metro rely more on external platforms and financial instruments, emphasizing accountability through program structure rather than operational control. Each approach reflects different institutional capacities and levels of comfort with private-sector involvement.

Ultimately, these agencies illustrate that TNC collaborations are not only cost-saving experiments but also strategic tools for expanding the social reach of public transportation. Whether enhancing coverage in industrial zones, enabling access for unbanked riders, or supporting night-shift workers, such partnerships redefine public service in a multimodal landscape. The interviews highlight a transition from early experimentation to institutional maturity, in which agencies deliberately use private platforms, guided by data, policy goals, and equity commitments rather than novelty or crisis response.

7.3. Challenges, Solutions, and Benefits of Transit–TNC Partnerships

The preceding sections highlighted how U.S. transit agencies have partnered with TNCs to expand coverage, enhance flexibility, and reduce operational inefficiencies. Through both national examples and detailed interviews with agencies like DART, LA Metro, and PSTA, it became clear that these partnerships are not just isolated experiments but emerging components of a broader mobility ecosystem. That said, a large number of transit agencies still remain skeptical of the benefits from such partnership.

However, integrating private on-demand operators into public transit systems is far from straightforward. Beyond their promise of adaptability and cost efficiency, TNC-based models raise complex questions regarding reliability, equity, regulation, and sustainability.

This section synthesizes the key challenges, potential solutions, and benefits associated with these partnerships, drawing upon both empirical evidence and conceptual insights from the literature and practice.

Operational and Reliability Challenges: A primary operational challenge in TNC-based systems lies in the unpredictability of supply. TNC driver availability fluctuates based on time of day, weather (Brugger & Watts, 2021), and market incentives. During peak periods or driver shortages, passengers may face long wait times, trip cancellations, or service gaps. Such eventualities can weaken user confidence and limit TNCs' capacity to serve as dependable public-service providers.

Proposed Solutions:

- Advanced scheduling and predictive analytics can mitigate supply volatility. Allowing riders to pre-book trips enables operators to forecast demand (such as in (Yi Hou et al., 2019)), allocate drivers, and reduce idle time.
- Performance-based contracts between transit agencies and TNCs should specify minimum service levels, fare ceilings, and subsidy mechanisms, ensuring reliability and affordability.
- Hybrid service models, in which dedicated agency-operated microtransit vehicles cover baseline demand while TNCs absorb overflow or off-peak requests, can stabilize service without excessive cost.

The partnership model proposed in this research assumes a pre-requested ride system, in which riders book their TNC trips in advance rather than relying on on-demand availability. This approach allows the system to assign drivers ahead of time, reducing the uncertainty associated with serving low-demand areas and preventing this challenge.

Additionally, because drivers accept the assignment prior to the trip, they are guaranteed a fare, helping stabilize supply and reducing the operational inefficiencies typically seen in low-demand substitution scenarios.

Equity and Accessibility Concerns: Digital access and vehicle design pose substantial equity barriers. Many potential users, including seniors, low-income residents, or individuals without smartphones or credit cards, struggle to access app-based TNC services. Wheelchair users often find few accessible vehicles, and privacy concerns may deter passengers who are uncomfortable sharing personal or location data.

Proposed Solutions:

- Alternative access channels: Establish phone booking options, prepaid ride vouchers, or the ability to link payments to transit smart cards (such as LA Metro Mobility wallet).
- Accessibility audits and targeted fleets: Conduct user surveys to assess demand for wheelchair-accessible rides and deploy small paratransit fleets or contracts with specialized providers (Gebresselassie, 2023).
- Digital inclusion initiatives: Partner with community organizations to offer training on TNC use and co-design features with vulnerable groups.
- Data privacy safeguards: Require only minimal personal information, allow optional "virtual stops" to protect home addresses, and adhere to public-sector data standards.

Such approaches ensure that technology integration does not inadvertently exclude the very populations public transit aims to serve.

Environmental and Logistical Issues: Replacing large fixed-route buses with smaller, on-demand vehicles can increase VMT and emissions if trips are poorly coordinated or

lightly occupied (Martin et al., 2024). Similarly, adding pickup points near stations may cause curbside congestion and operational conflicts.

Proposed Solutions:

- Restrict TNC parnership to low-demand areas and off-peak hours, where replacing empty buses with smaller vehicles yields net efficiency gains.
- Encourage or require the use of electric or hybrid vehicles, supported by charging infrastructure near transit hubs (Jenn, 2024).
- Employ integrated scheduling platforms that coordinate TNC arrivals with bus departures to minimize idle travel and reduce emissions.
- Design mobility hubs with designated pickup areas to prevent curbside bottlenecks and improve safety.

By integrating environmental planning with operational coordination, agencies can ensure that flexible mobility supports sustainability goals. This study proposes a partnership that operates in low-demand and off-peak periods and incorporates pre-requested rides to reduce or eliminate wait times at transfer points. Pre-allocating trips limits roaming and empty travel, reducing unnecessary mileage. Additionally, truncation points are chosen based on physical feasibility for redirecting buses, ensuring they can also accommodate short-term TNC stops and enable smooth, efficient transfers

Financial and Pricing Challenges: The dynamic pricing models used by TNCs create uncertainty for both riders and agencies. Surge pricing during high demand can make fares unaffordable, while drivers may favor lucrative areas, leaving low-income neighborhoods underserved.

Proposed Solutions:

- Contractual price ceilings and pre-negotiated flat rates prevent excessive fares while maintaining fair compensation for drivers (Nandi, 2020).
- Subsidies for low-income and low-demand areas can promote equity, financed through savings from reduced fixed-route operations.
- Public-private investment models or cost-sharing frameworks can distribute financial risk while aligning incentives for service quality.
- Performance-linked payments to TNCs based on reliability and coverage metrics encourage consistent service delivery.

The proposed operation occurs in low-demand areas and during off-peak times, which reduces the likelihood of surge pricing triggered by high request volumes. To further manage cost uncertainty, transit agencies should establish clear contracts with TNC partners that define payment structures in advance and specify how external factors such as weather-related price increases will be handled. In this model, rides are assumed to be fully subsidized at the level of the existing bus fare, ensuring that passengers are not exposed to unexpected or additional costs.

Policy, Regulation, and Labor Issues: TNC partnerships raise regulatory questions around liability, insurance, data ownership, and labor standards. Conflicts may arise between unionized transit workers and TNC drivers, who often operate as independent contractors under different employment protections (National Academies of Sciences, 2016).

Proposed Solutions:

- Develop comprehensive partnership contracts defining responsibilities, insurance provisions, and data-sharing requirements (California Public Utilities Commission, 2025).
- Pursue collaborative policymaking that balances innovation with worker protections, potentially including training opportunities or minimum-earnings guarantees for participating drivers (Department of Labor and Industry, 2025).
- Maintain clear accountability frameworks, ensuring that the public agency retains oversight over service quality, safety, and equity outcomes.

The contract structures proposed in this study ensure that TNC drivers are compensated at or above minimum wage. Addressing this and other operational challenges is feasible only when supported by a clear, detailed, and well-defined contract.

Technological and System Integration: Effective coordination between public transit and TNC platforms requires advanced data sharing and interoperability. In many regions, differing software systems, fare structures, and data standards make seamless operation difficult.

Proposed Solutions:

- Implement shared technological platforms or APIs that integrate trip planning, booking, and payment across TNC and transit services (Federal Transit Administration, 2019).
- Adopt real-time data-exchange protocols to synchronize routes, manage transfers, and enable dynamic rerouting during service disruptions.

- Develop unified fare systems through mobility-as-a-service (MaaS) applications, allowing users to pay for multimodal trips through a single interface (Hansen et al., 2018).

Such integration improves the rider experience and provides agencies with data needed for ongoing optimization. The contract should clearly specify responsibility for managing and supporting the shared technology.

Marketing, Communication, and Public Awareness: Even well-designed systems can fail without public understanding and acceptance. Riders accustomed to traditional transit may be hesitant to adopt new, app-based mobility options.

Proposed Solutions:

- Launch pilot programs or transitional phases where TNC services operate alongside existing routes, allowing riders to adjust gradually.
- Use targeted outreach campaigns through stations, social media, and community organizations to explain how to book rides and use subsidies (Board & National Academies of Sciences and Medicine, 2019).
- Collect user feedback during pilots to refine pricing, pickup points, and service coverage before full implementation (Wang & Shen, 2024).

Strong communication builds user trust and ensures smoother adoption of hybrid mobility systems.

Passenger Comfort, Safety, and Perceived Disutility: Sharing rides in small vehicles can create discomfort for longer trips, especially when transfers are required. Riders accustomed to direct, high-capacity transit may perceive such changes as inconvenience.

Proposed Solutions:

- Design transfer hubs that minimize walking distances, provide shelter, and ensure lighting and security (Darling et al., 2023).
- Align schedules to reduce transfer waiting times and maintain real-time coordination through app notifications.
- Provide clear information on trip progress and estimated arrival to reinforce reliability and safety perceptions (Gangadharaiah et al., 2023).

While shared rides inherently differ from fixed-route service, attention to comfort and communication can significantly reduce perceived inconvenience.

Long-Term Planning and System Coordination: Sustaining TNC-based programs requires ongoing coordination with the broader transit network. Without careful planning, resource allocation between buses, trains, and on-demand services may become inefficient.

Proposed Solutions:

- Replace deterministic ridership assumptions with stochastic demand modeling, capturing variability in boarding and alighting patterns (Liu et al., 2025).
- Optimize bus route design and determine where fixed routes can be truncated or redesigned to complement TNC coverage.
- Evaluate whether trip grouping and dispatch should be managed by the transit agency or the TNC, depending on contractual flexibility and data access.
- Conduct periodic performance reviews to adjust service boundaries and ensure alignment with demand and policy goals.

Despite these challenges, integrating TNCs into transit networks offers numerous potential benefits when implemented strategically. The benefits which will be discussed below are supported by several sources, such as: (Grahn et al., 2023) , (Federal Highway Administration, 2021), (Midthun, 2025)(Midthun, 2025) , (T. Ma et al., 2019) , (Board & National Academies of Sciences and Medicine, 2019) , and (Darling et al., 2023).

Operational Flexibility and Coverage Expansion: TNCs provide door-to-door, on-demand mobility that extends service into low-density or previously unserved areas. By matching supply to demand in real time, agencies can maintain coverage without operating empty or infrequent buses.

Improved Accessibility and Safety: Door-to-door trips eliminate walking distances, benefiting seniors, individuals with disabilities, and passengers traveling at night. The reduction in time spent at stops or parking lots enhances personal safety and convenience.

Cost Efficiency and Resource Optimization: Replacing or supplementing low-productivity routes with TNCs can significantly reduce operating costs. Savings can be reinvested as subsidies, improving affordability and extending service hours.

Reduced Wait Times and Faster Travel: On-demand rides minimize waiting and allow more direct routes than traditional buses with multiple stops. Scheduled rides further enhance time savings for commuters and those with fixed appointments.

Extended Hours and Off-Peak Service: Unlike traditional routes constrained by schedules and labor limits, TNCs can operate late at night or early morning, ensuring mobility during non-traditional work hours and improving access for shift workers.

Enhanced Network Connectivity: By filling first- and last-mile gaps, TNCs can increase total transit ridership, encouraging multimodal trips rather than competition between modes.

Environmental and Urban Design Benefits: When paired with electric or hybrid fleets, shared rides can lower per-capita emissions and reduce parking demand near transit hubs. Freed land can be repurposed for green space or mixed-use development, enhancing urban livability.

Social and Economic Inclusion: Improved accessibility supports job retention, education, and healthcare access for low-income and mobility-limited populations. Formalized partnerships may also create new, more stable driving opportunities within the local economy.

Institutional Innovation: TNC partnerships push agencies to adopt modern technologies such as real-time data systems, integrated payment platforms, and demand-responsive operations, laying the groundwork for future autonomous and sustainable mobility solutions.

CHAPTER 8: Conclusions

Public transit systems exist because society often argues that mobility should be considered a public good. Public transit agencies' mandate is not to generate profit but offer accessible transportation: ensuring that people can reach work, school, healthcare, and community regardless of income, neighborhood density, or peak demand patterns. That mission, however, creates tension. Transit agencies must often operate full-size buses on route segments where only very few riders board, sometimes fewer than four riders over an entire multi-mile segment of a bus trip. These low-productivity segments are not mistakes; they reflect equity and coverage goals. But they impose disproportionate operating costs and consume vehicle and driver resources that could be used to strengthen frequency elsewhere with higher ridership and high induced-demand potential. Agencies thus face a difficult decision: preserve coverage by running nearly empty buses or remove service and risk isolating transit-dependent riders. The emergence of flexible, on-demand TNCs introduces a potential third option, not as a replacement for transit, but as a tool for targeted use in low-demand contexts, as demonstrated by the data-driven evaluation in this research.

The work began with a simple observation grounded in data: demand is not uniform along fixed bus routes. Some stops consistently show activity; others show none at all. Instead of labeling an entire route as productive or unproductive, this research assessed ridership at the stop and route-segment level. Passenger boarding activity revealed stretches where buses traveled several miles without meaningful ridership. For example, in Long Beach, CA, in several cases, buses traveled more than 2.7 miles with zero boardings. Agencies lack a systematic method to identify the inefficient segments that are candidates for cost-effective TNC-substitution. To address this, a screening approach was developed using two

data sources (GTFS and APC counts). It highlights segments with very low passenger density, inactive stops, and long distances between meaningful boardings. This method alone shifts agency practice. Rather than just knowing where inefficiencies might be, planners can see exactly where less costly alternate service possibilities exist.

Identifying low-demand locations was only the first step. The harder question was whether an alternative service could serve these riders effectively and affordably. Serving these riders through on-demand vehicles introduces operational complexities: dispatch coordination, ride matching, pooling potential, and compensation expectations for both driving and waiting time. To move beyond conceptual speculation, an optimization model was constructed that simulated real operational conditions. The model represented the mechanics of a contracted TNC system: how many vehicles would be required, how rides could be pooled, and what the total cost to the agency would be. Across multiple simulated days of service, demand patterns showed that for low-demand bus segments serving 1–4 riders, only 1–2 on-demand vehicles were required, even during the highest demand peaks.

Application of the optimization model yielded a critical insight: contract structure and its cost parameters determines feasibility. If drivers are compensated by the hour regardless of activity, pooling efficiency drops and costs increase. This means that cost savings do not come from “ride-hailing” itself but from aligning financial incentives with efficient routing. Under the wrong contract structure, on-demand service becomes more expensive than a bus. Under the right structure, it becomes a tool that preserves access while reducing waste. Results from the Long Beach Transit case study show that segment truncation with TNC substitution can reduce operating costs on the selected line by up to 60% while improving passenger utility by approximately 50% during the selected low-demand periods. Even in

cases where the substitution is not financially advantageous, improvements in passenger utility may justify adopting the system.

The research next examined design decisions that shape the rider experience and compared them with suggested door-level service. Substitution can be implemented in multiple ways. Agencies may require riders to walk to designated stops (or bus stops) within the substituted segment or offer true door-to-door pickup. The design choice affects cost and convenience differently. In the door-to-door scenario, riders experienced no walking time and reduced overall travel time. In the stop-based scenario, riders were required to walk 3–8 minutes to a designated pick-up location, lowering cost slightly, though it would conceivably worsen perceived access. An alternative (subsidizing independent TNC rides) reduced travel time by 10–18 minutes compared to the bus, but increased cost because the agency subsidized full market-rate fares. In another comparison, this research showed that demand responsive transit can also be a good option compared to the traditional bus (up to 50% saving), but TNC operate more productively under low-demand condition. The lesson is clear: TNC substitution is not simply a routing exercise with an off-the shelf optimization algorithm; it is an expression of agency priorities. Whether the objective is cost reduction or rider convenience – a policy decision – fundamentally shapes the outcome.

Even with these insights, agencies cannot build an optimization model every time they consider a route change. They need a fast, predictive way to determine whether substitution is financially worthwhile. The research developed models using simple route characteristics such as passengers per mile, passengers per stop, and number of inactive stops. Several bivariate analyses were conducted. A clear threshold emerged: substitution is consistently cost-effective when passenger density is below approximately 0.5 passengers

per stop or 3.5 passengers per mile. Below this level, on-demand service reduces cost; above it, bus service becomes more efficient. These metrics do not dictate decisions; they enable evidence-based ones.

While modeling reveals what is possible, real-world pilots reveal what is practical. Multiple agencies have experimented with on-demand substitutions. Programs in Dallas, Los Angeles, and Pinellas County show that this approach works when the agency retains control over the rules of operation. In Dallas, zone-based microtransit combined agency vehicles with TNC supply and maintained performance by keeping dispatch control. In Los Angeles, CA, a prepaid Mobility Wallet ensured that unbanked riders could use app-based modes. In Pinellas County, FL, differentiated subsidy programs improved late-shift worker access. These cases show that success depends less on which mode is used and more on how the program is designed.

TNC substitution is not about shrinking transit services. It is about preserving access while reducing waste. Substitution frees resources trapped in low-productivity service and allows agencies to reinvest those savings into improving high-demand corridors. Riders benefit from faster trips and reduced walking. Agencies benefit from lower operating costs and the ability to redirect service to places where demand actually exists. Drivers benefit when contract rules guarantee fair compensation and minimize idle time.

While this research establishes a framework for identifying low-demand segments and testing the feasibility of on-demand replacement, it also opens several promising directions for future work. One natural extension is to examine how agencies can reinvest the time and mileage released from low-productivity service into other parts of the network. Future research could build a joint scheduling model that reallocates the “saved” bus hours

from substituted segments and reinserts them into high-demand corridors, iterating bus and TNC deployment until reaching a network equilibrium that maximizes overall system efficiency. Such a model could provide insight into the system-wide benefits of substitution, including increased frequency and improved reliability on high-demand route-segments. This can increase ridership, which is an important goal of transit agencies.

Another direction involves improving the representation of travel behavior and uncertainty. In this dissertation, demand was treated as known based on historical patterns, but actual demand fluctuates. Introducing stochastic demand, where passenger arrivals vary within a realistic range, would help evaluate operational robustness. Similarly, incorporating dynamic or semi-dynamic booking (for example, allowing passengers to request trips a certain number of minutes in advance) would provide insight into how early riders need to initiate a request for the system to function efficiently. This would allow future researchers to explore how far ahead riders are willing to schedule a trip and whether early request windows improve pooling. Expanding the analysis to multiple networks and cities would also strengthen the findings. Different land-use patterns, socio-demographic characteristics, and cultural attitudes toward ride-hailing could influence the level of adoption and cost efficiency. Some communities may embrace TNC substitution quickly; others may prefer agency-operated demand-responsive service. Real-world piloting will be essential to studying these behavioral effects. A pilot study could follow the framework developed in this dissertation and observe how riders respond to the new service.

Future research could also examine broader impacts, such as environmental effects. Even if only one or two small vehicles replace a bus, emissions savings will depend on pooling success and deadheading distance. Quantifying changes in VMT, fuel use, and carbon

emissions would provide environmental justification alongside financial justification. More applied studies could address operational aspects that agencies will eventually face: app integration, payment methods for riders without smartphones, customer support or call-center configurations, real-time communication between bus and TNC dispatch, and equity mechanisms such as fare caps or income-based subsidies. Finally, there is a behavioral dimension that has not yet been explored: how substitution affects mode choice and whether it generates new demand. Offering door-to-door service may attract discretionary riders who would not have taken the bus at all. Understanding whether that "secondary demand" is desirable or whether subsidy levels should be adjusted to avoid overspending is an area ripe for research. Currently, the substitution concept assumes riders pay only their bus fare; future studies could examine how varying levels of subsidy or fare structure affect rider decision-making and perceived utility similar to work done by Saha et al. (2025) for microtransit.

A main contribution of this research is at the conceptual level. It questions the notion that a full-size bus must operate everywhere, simply because it generally always has. It reframes substitution not as an abandonment of service but as an evolution of service strategy. Transit is irreplaceable in moderate- and high-demand corridors; that is where the bus is most efficient, equitable, and essential. But in extremely low-demand contexts, where the mission is preserving access rather than moving large numbers of people, flexibility can protect service rather than threaten it. TNC substitution enables agencies to uphold coverage goals while being responsible stewards of limited public resources.

The question facing transit agencies should no longer be "Bus or TNC?" The question must become: "What is the best tool for serving this rider, at this time, in this place?"

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APPENDIX

Questionnaire:

What motivated your agency to partner with a Transportation Network Company (TNC)?

Who was the intended user group, and what specific service gaps or challenges were you aiming to address through this partnership?

What challenges did you face in launching the TNC partnership and attracting ridership?

What were the primary concerns or barriers reported by passengers during the rollout?

How is the TNC-integrated service performing?

Has it led to improvements in ridership, accessibility, or cost-efficiency? If the program was discontinued, what were the main financial, operational, or policy-related reasons?

Are you able to share any available data on the program's financial structure or performance?

For example, budget allocation, contract terms, number of users, or common trip purposes.

How was the service designed in terms of coverage, hours of operation, and integration with the existing transit network?

What role did equity, geography, or trip purpose play in shaping the design?

How was fare integration handled between the TNC and the transit system?

Were there subsidies, discounts, or app-based solutions to ensure a seamless experience for riders?

Were there any regulatory, legal, or union-related challenges in implementing the partnership?

How were these addressed?

What lessons were learned through the pilot or program that might inform future microtransit or TNC partnerships?

What would you do differently if you were to launch a similar program today?