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Mobility Trends in New York City's Outer Boroughs Post Enhanced Taxi Coverage.

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As a part of the Work Project "Urban Transportation in New York City: A Comparative Analysis of Accessibility, Pricing, and Usage Trends" with ANGELINA SUCHKOVA, WALE DOURA, MASSIMO PIO CAROLLO, LAURENZ VON PERBANDT

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Abstract (Group)

This thesis examines the interplay across diverse mobility options in New York City, focusing on cost variability and commuter behavior. This work investigates the evolution of fare disparities between taxis, using comprehensive datasets from NYC's Taxi and Limousine Commission, along with advanced predictive modeling approaches such as Long Short-Term Memory and Gradient Boosting. The study revealed how commuter choices are influenced by operational regions and pricing models: key findings highlight significant temporal and spatial fare trends. Enhanced taxi coverage in NYC's outer boroughs has led to a measurable shift in subway ridership. Green Taxis, designed to address transportation gaps in underserved neighborhoods, exhibit limited success, particularly in low-income areas, where reliance on private vehicles remains dominant. Additionally, a comparative analysis of dynamic versus fixed pricing models showcased the flexibility of ride-hailing platforms like Uber in addressing peak demands and spatial variations, differing from the rigidity observed in traditional pricing systems. These analyses provide critical insights into spatiotemporal variations in taxi demand, including the differential impacts of public transit availability and demographic factors.

By addressing pricing disparities and enhancing service accessibility, this work concludes by presenting actionable recommendations to improve equity and efficiency within NYC's transportation network. The findings aim to guide policymakers in developing adaptive and sustainable mobility strategies tailored to the evolving urban landscape.

Abstract (Individual)

New York City (NYC) has long been defined by its robust public transit network, yet the outer boroughs—Brooklyn, Queens, the Bronx, Staten Island, and Upper Manhattan—have historically experienced limited access to traditional Yellow Taxi services. In response, the city introduced Green Taxis in 2013 to enhance taxi availability outside Manhattan, coinciding with the rise of ride-hailing services like Uber and Lyft. This study investigates the impact of enhanced taxi coverage on mobility trends in NYC's outer boroughs, focusing on subway usage, congestion levels, and private car ownership. Using data from the NYC Metropolitan Transportation Authority (MTA), the Taxi and Limousine Commission (TLC), and automated traffic volume counts, this research examines geo-specific mobility patterns. The findings indicate that subway ridership has increased in higher-income areas such as Manhattan, while it has declined in middle-income neighborhoods, particularly in Brooklyn and Queens, where reliance on taxis and private cars has grown. Green Taxis, initially designed to improve outer borough transportation, have seen a decline in ridership, overshadowed by the rapid expansion of ride-hailing services. Additionally, congestion has worsened, especially in Brooklyn and Queens, with a notable increase in private car ownership. These trends suggest a shift towards greater car dependency in NYC's outer boroughs, challenging the sustainability of public transit. The study underscores the need for city planners to enhance subway reliability, expand non-motorized travel infrastructure, and reconsider the effectiveness of Green Taxis in alleviating transit gaps. Addressing these mobility challenges is crucial for promoting a balanced and efficient urban transportation system in NYC.

Table of Content

Group Work with ANGELINA SUCHKOVA, WALE DOURA, PARAM SUMIRAN, LAURENZ VON PERBANDT MASSIMO PIO CAROLLO

Table of Figures

1. Introduction

Urban mobility systems are critical to the functioning of modern cities, enabling the movement of millions of individuals daily while shaping economic, social, and environmental outcomes. In New York City (NYC), a city renowned for its dense population and complex infrastructure, transportation services play a pivotal role in supporting urban life. Over the years, NYC's transportation landscape has evolved significantly, reflecting changes in commuter needs, technological advancements, and policy-driven reforms. Central to this system are its taxi services, which range from traditional yellow and green taxis to app-based ride-hailing platforms like Uber and Lyft, and the broader network of public transit systems such as buses and subways.

Despite this diversity, challenges such as geographic inequities, congestion, and fluctuating demand persist, necessitating a deeper understanding of how different mobility modes interact and adapt within the city's unique urban environment. Efforts to expand and diversify NYC's transportation network have resulted in significant changes to its taxi ecosystem. Historically dominated by yellow taxis, the introduction of green taxis sought to extend services to underserved areas like Brooklyn, Queens, and the Bronx. These changes raised questions about how increased taxi coverage has influenced commuter behavior in the outer boroughs. Has this initiative successfully addressed gaps in accessibility, or has it merely shifted existing dynamics? Understanding these spatial patterns offers insights into the effectiveness of such policy-driven expansions.

At the same time, the interplay between public transit systems and taxi services highlights the interconnectedness of NYC's mobility ecosystem. Public buses, often serving as a lifeline for disadvantaged communities, experience competition and complementarities with taxis, especially in areas where subway access is limited. Changes in bus service availability, delays, or coverage can influence taxi usage, creating ripple effects across the transportation network.

Exploring these dynamics sheds light on how public and private modes of transport coexist and compete within a constrained urban space.

Pricing models further complicate NYC's mobility landscape. The cost differences between yellow and green taxis provide a lens to examine how operational areas and fare structures influence commuter choices. These variations reflect not only economic factors but also temporal and spatial nuances, revealing how fares align—or fail to align—with demand patterns. While green taxis aim to serve peripheral neighborhoods, the cost dynamics between the two services prompt questions about fairness, efficiency, and accessibility. The emergence of app-based ride-hailing services such as Uber and Lyft has introduced new layers of complexity to NYC's transportation system. These platforms, offering flexibility and convenience, cater to a wide range of travel purposes, from routine commutes to leisure activities. By comparing trip patterns between green taxis and ride-hailing services, it is possible to uncover how user preferences and behaviors diverge across different modes. These insights are critical for understanding the broader implications of these services on traditional taxi operations and commuter mobility.

Underlying many of these discussions is the tension between fixed and dynamic pricing models. Traditional taxis operate under regulated pricing systems, offering predictability but limited adaptability to changing conditions. In contrast, ride-hailing platforms leverage dynamic pricing algorithms to adjust fares in real time based on demand and traffic. These distinct approaches offer a unique opportunity to explore how pricing strategies influence fare sensitivity and commuter decision-making, especially in a city as multifaceted as NYC. This is why this thesis investigates several interconnected research angles of New York City's transportation systems: by examining the evolution of fare disparities between yellow and green taxis, along with employing advanced predictive models to understand cost variations over time and space, it was possible to show high variability in cost differences between comparable taxi rides and the consequent difficulty in predicting those values. Additionally, green taxis primarily serve outer boroughs with stable fares, while yellow taxis dominate central Manhattan, often with higher and more variable costs during peak hours and weekends, highlighting how operational zones and service shape commuter behavior. Moreover, this study reveals how shifts in taxi coverage influence subway ridership in underserved areas of NYC. Another aspect involves evaluating the impact of dynamic pricing models as seen in ride-hailing platforms like Uber and contrasting them with traditional systems used by taxis. This led to a deep understanding of flexibility and efficiency in addressing peak demand and spatial variability.

2. Literature Review

2.1 Foundations of Urban Mobility

Urban mobility describes the systems, services, and infrastructure that enable the movement of people and goods within urban areas. It is defined as the integration of multiple transportation modes, such as public transit, private vehicles, shared mobility, walking, and cycling, and it aims to address challenges of accessibility, sustainability, and equity. Its scope comprises multimodal systems for seamless travel, sustainability efforts to reduce environmental impact, and the adoption of advanced technologies like AI and ICT to improve efficiency and user experiences. An important aspect of urban mobility is to ensure economic and social equity, making transportation affordable and accessible for all residents while balancing environmental and economic goals (Arthur D. Little, 2011). The evolution of urban transportation systems was influenced by sociopolitical and historical developments. In pre-20th-century cities, compact and walkable designs dominated, with limited mechanized transport. The post-war era saw a surge in car ownership, resulting in investments in road networks and the neglect of tram systems in many urban areas. However, some cities, such as Karlsruhe, maintained and innovated tram networks, in contrast to car-centric developments in other cities. The late 20th century saw a rebirth of interest in sustainable transit, which led to innovations like tram-train systems and integrated urban planning (Pflieger, 2009). To this day, private cars remain dominant globally, accounting for 45% of trips. However, projections suggest a 15% decline by 2035, driven by the growth of autonomous vehicles and micromobility (McKinsey & Company, 2023). Urban transportation systems show path dependencies, where historical decisions, such as the introduction or removal of tram systems or the growth of private car ownership, create lasting influences on urban policies and infrastructure. The high cost of reversal locks cities into specific development trajectories unless significant crises or innovations occur (Pflieger, 2009). New York City shows unique urban mobility characteristics shaped by its geography and central transportation hubs. Sustainable transportation modes, such as walking, biking, and public transit, account for more than two-thirds of all trips. NYC's dense urban cores, particularly in Manhattan and key business districts, play a critical role in that. The Central Business District (CBD) experiences heavy congestion, with sustainable transportation accounting for 78% of trips into the area. Public transit remains vital for most residents, although aging infrastructure and telecommuting have caused slight declines in subway use (New York City Department of Transportation, 2019). Programs like Citi Bike illustrate the emergence of micromobility, reshaping short-distance travel in areas like Midtown Manhattan (Sun & Axhausen, 2016).

NYC's mobility patterns reflect interconnected yet constrained boroughs, with bridges and tunnels serving as critical, often congested nodes. The growth of freight and e-commerce is adding pressure to urban traffic systems. Geographical constraints, such as the city's island structure, limit road expansion and shift the focus to efficient public and shared transportation. Additionally, high tourist volumes, especially in areas like Times Square, require special mobility solutions for localized travel (New York City Department of Transportation, 2019).

2.2 Role of Taxis in NYC's Urban Mobility

Taxis have been a significant part of New York City's transportation landscape for decades. They serve as a key alternative to public transit, particularly in areas with limited-service coverage, and for seniors and individuals with mobility challenges (New York City Department of City Planning, 2009). Historically, NYC's taxi system was governed by the medallion system, which regulated the number of cabs operating within the city. However, the rise of app-based ride-hailing services, such as Uber and Lyft, has caused a significant decline in traditional yellow taxi usage, reshaping urban mobility patterns and changing urban transportation planning. The transition from medallion taxis to ride-hailing services indicates a broader shift in consumer preferences, technological adoption, and the evolving role of taxis in the city's transportation structure (Moro, 2021; New York City Department of City Planning, 2009). This changing landscape has significant implications for urban planning and mobility strategy in NYC. As ride-hailing services increasingly dominate, the city must address issues of equity, congestion, and sustainability to ensure that taxis, both traditional and app-based, continue to contribute effectively to the broader transportation network (Moro, 2021).

2.3 Socio-Economic and Demographic Factors Influencing Urban Mobility in NYC

Income inequality significantly impacts access to transportation options in New York City, showing mobility inequalities among different socio-economic groups. Lower-income individuals face barriers, such as high taxi costs and inconsistent public transport availability in underserved neighborhoods, limiting their ability to access essential services like jobs and healthcare (New York City Department of City Planning, 2009). In contrast, wealthier residents benefit from better access to diverse transportation modes, including taxis and ride-hailing services, and are more likely to explore geographically diverse areas, reducing experienced segregation (Moro, 2021). High-income areas, particularly in central Manhattan, are dominated by yellow taxis, while peripheral and low-income areas often rely on less reliable livery cabs or limited public transit options, deepening mobility inequalities (New York City Department of City Planning, 2009). This dynamic reinforces systemic segregation and unequal access to opportunities, as residents in these areas face constraints tied to economic and infrastructural limitations (Moro, 2021). Work-from-home (WFH) and hybrid work models have also transformed commuting patterns in the city. While these models have reduced rush-hour congestion, they have increased off-peak traffic, particularly in areas with flexible work environments. This shift required adaptations in transit schedules and infrastructure to adapt to the changing traffic flows (Lasley, 2021).

2.4 Public Policy and Governance in Urban Mobility

By aiming to address social equity, environmental sustainability, and technological advancements, public policy and governance play a critical role in shaping urban mobility systems. While stable political regimes rather reinforce existing policies, institutional and political changes either strengthen innovation or serve as barriers to reform. Urban transport policies, such as integrated planning in cities like Grenoble, demonstrate how aligning transportation with urban development can result in significant social and spatial benefits, including reduced car reliance and improved accessibility (Pflieger, 2009). Urban and transport planning also have direct health implications. Proper planning can mitigate key urban exposures, such as air pollution, noise, and urban heat islands, while enhancing access to green spaces and opportunities for physical activity (Nieuwenhuijsen, 2016). Community-level interventions, such as promoting green spaces and reducing car reliance, have proven more cost-effective and impactful than individual-level efforts. These strategies emphasize equitable access to transport systems, bridging the gap between income-segregated communities by expanding affordable public transit and reducing cost barriers for taxis (Moro, 2021). In New York City, regulation is a key tool for managing mobility challenges. The medallion system historically controlled the taxi industry, while congestion pricing programs are now being introduced to reduce vehicle volumes in the Central Business District (Miskolczi, 2021; New York City Department of Transportation, 2019). Cities worldwide are adopting similar measures, including parking restrictions, car-free zones, and dynamic tolling, to manage traffic and pollution. Such strategies are crucial in balancing technological

advancements with societal acceptance and legal frameworks, especially for innovations like autonomous vehicles (Bouton,2015).
Public-private partnerships (PPPs) further address urban mobility challenges by fostering collaboration between governments, private companies, and tech innovators. These partnerships accelerate the deployment of solutions like electric vehicle (EV) charging stations, shared mobility platforms, and autonomous vehicle (AV) pilot projects. For example, governments can subsidize shared mobility services, provide tax benefits for EV adoption, and promote subscription-based services to encourage behavioral shifts toward sustainable mobility (Miskolczi,2021;Butler,2020;Kamargianni,2016).
Finally, governance frameworks must address data privacy and transparency, ensuring user trust while leveraging mobility data for planning and optimization. Policies supporting AV integration, such as liability guidelines and safety standards, can build public confidence and accelerate adoption (Miskolczi, 2021). By investing in intelligent transportation systems (ITS), high-speed internet, and secure communication networks, cities can establish the foundations for smart infrastructure and future-ready urban mobility systems (Butler, 2020).

2.5 Technological Innovations and Smart Mobility in NYC

Technological innovation in urban mobility is expected to play an important role in dealing with the growing transportation challenges. Over-reliance on private vehicles and outdated infrastructure is pushing many urban mobility systems toward breakdown. To address these challenges, advancements in automation, shared mobility, and electrification are transforming urban transportation systems (Miskolczi, 2021). Services like Uber and Lyft have revolutionized urban transit by introducing e-hailing, car sharing, and on-demand shuttles. These innovations are driving a decline in car ownership, especially among younger generations in developed nations, as preferences shift toward shared mobility. Mobility-as-a-Service (MaaS) platforms exemplify this transformation by integrating public transit, car sharing, and bike-sharing into a single, seamless system (Bouton, 2015). Through real-time data sharing and journey planning, MaaS offers door-to-door mobility while reducing reliance on personal vehicles (Butler, 2020). However, its implementation faces challenges, such as limited integration across operators, complex revenue-sharing models, and varied user willingness to pay for subscription-based services (Kamargianni, 2016). Shared mobility services, including dockless bike-sharing programs and app-based ridesourcing, address critical issues like first- and last-mile connectivity. They also deliver environmental benefits by reducing vehicle miles traveled and decreasing road congestion. These innovations are key to strengthen multimodal travel, sustainability, and urban accessibility (Butler, 2020). Emerging technologies like big data and the Internet of Things (IoT) are central to modern urban traffic management. Inefficiencies in urban mobility currently cost cities 2–4% of their GDP due to wasted time and resources (Bouton, 2015). Intelligent Transportation Systems (ITS) integrate advanced ICT and real-time analytics to optimize transportation networks. Applications include adaptive traffic signal control, incident detection, and dynamic scheduling for public transit. Additionally, networked ecosystems, such as vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) systems, promise enhanced safety and traffic flow (Lasley, 2023; Moss, 2012; Butler, 2020).

The transition to electric and autonomous vehicles (AVs) is redefining urban mobility. Electric vehicles (EVs) significantly improve energy efficiency and reduce emissions (Moss, 2012; Bouton, 2015). Meanwhile, AVs, capable of navigating without human input, hold the potential to reduce road accidents by up to 90%, increase traffic efficiency, and provide mobility options for individuals without driving licenses. However, challenges, such as cybersecurity risks, ethical dilemmas during accidents, and infrastructure readiness, remain significant barriers to widespread adoption (Butler, 2020). Adoption might remain slow due to economic and social barriers, which highlights the need for regulatory clarity and collaborative efforts across sectors (Bouton, 2015). Crucial for supporting these innovations are investments in smart infrastructure, including electric vehicle charging networks and data processing for traffic management (Moss, 2012).

2.7 Comparative Studies and Lessons from Other Cities

New York City may benefit from examining sustainable and innovative mobility practices implemented in other global cities. One significant area of innovation is the development of Mobility-as-a-Service (MaaS) platforms. Cities like Helsinki and Gothenburg have pioneered MaaS initiatives, such as UbiGo, which integrate various transit modes into a single, seamless system. These platforms allow users to plan, book, and pay for multi-modal journeys across different transport providers, simplifying access to sustainable transport and reducing reliance on personal vehicles (Bouton, 2015; Kamargianni, 2016). Other examples of successful MaaS implementations include the Octopus card in Hong Kong and the Oyster card in London. These smart card systems have significantly increased public transit usage by offering a unified payment method for various modes of transportation, including buses, subways, and ferries. The convenience and efficiency provided by these integrated systems highlight the potential for MaaS to transform urban mobility by promoting multimodal travel and making public transportation more user-friendly (Butler, 2020). However, transferring global best practices to New York City's context requires careful consideration of the city's unique characteristics. Different city types—such as megacities, rising cities, and car-dominated cities—experience unique mobility evolutions based on factors like density, existing infrastructure, and available resources. For instance, while NYC shares similarities with other megacities in terms of scale and complexity, its legacy infrastructure and regulatory environment may present challenges not encountered in cities like Helsinki or London (Bouton, 2015).

2.8 Emerging Trends and Future Challenges in Urban Mobility

Urban mobility is experiencing significant transformations driven by emerging trends and future challenges. By 2030, 60% of the global population will live in cities, intensifying pressure on urban infrastructure (Moss, 2012; Bouton, 2015). Integrating urban mobility with land-use planning is becoming essential for future development, ensuring that transportation systems align with urban growth strategies and environmental objectives (Bouton, 2015). There is a growing reliance on mixed transportation modes, including public transit, car-sharing, biking, and walking. This shift indicates urban residents' increasing preference for connectivity and access over private car ownership (Moss, 2012). Reallocating urban space is another emerging trend aimed at enhancing the quality of urban life. This involves repurposing areas previously dedicated to parking for green spaces, bike-sharing docks, or electric vehicle (EV) charging stations. Introducing car-free zones and low-emission areas helps reduce congestion and pollution, improving urban quality of life (Moss, 2012; Moskolczi, 2021). The traffic composition is also evolving. Congestion has increased due to the surge in e-commerce demand, leading to significant delays during peak periods, especially in densely populated urban areas (Lasley,2023).

Key challenges include the slow adoption of innovations due to economic and social barriers, the need for integrated infrastructure to support shared and autonomous systems, and balancing technological advancements with societal acceptance and legal frameworks (Miskolczi, 2021). These emerging trends and challenges highlight the necessity for cities like New York to adapt and innovate. Embracing integrated planning, promoting multimodal transportation options, and preparing for future demographic shifts are crucial steps toward creating a resilient and efficient urban mobility system.

3. NYC Transportation Industry Overview

3.1 The historical development of NYC’s transportation system

The transportation system of New York City lays the foundation of the world’s most dynamic city, reflecting centuries of technological development, policy experimentation, and adaptation. The system comprises ferries, buses, subways, and taxis and regularly makes more than 8.5 million trips each day to meet the needs of New York City’s growing population, tourism, and economy. We’re going to trace the development of NYC’s transportation system especially buses, subways, and taxis, providing the historical context needed to understand the interconnections and evolution of urban mobility in New York City.

Buses: From Horsepower to High-Tech

Beginning with horse-drawn omnibuses, NYC's bus system developed in the early 19th century. These basic buses traveled along fixed routes and charged fares of 12.5 cents, or $4.50 today. By the 1850s, omnibuses were being replaced by horse-drawn streetcars, allowing for more speed and capacity. Electric trolleys appeared in the 1880s, allowing a new era of mechanized transit.

Motorized buses hit New York City streets in 1907 with the Fifth Avenue Coach Company, offering a cleaner, more efficient alternative to horse-drawn systems. The city purchased private bus lines during the Great Depression and brought all operations under public control by the 1940s. By 1950, buses were carrying 2.3 million daily passengers, connecting neighborhoods often not served by the subway. Select Bus Service (SBS), introduced in 2008, modernized the bus network and reduced travel times by 20–30% with features such as off-board fare collection and dedicated lanes. By 2020, NY’s buses served 1.2 million daily riders, down from their mid-20th-century peak but still important for underprivileged areas. Recent efforts have turned to electrification; in 2022, the MTA announced that it planned to switch its entire fleet to zero-emission buses by 2040.

Subways: The Backbone of Urban Transit

The subway system, one of the most important components for public transportation, originates back to the overcrowded streets of the 19th century, where the trains or “El trains” provided the first solution. The first subway line, run by the Interborough Rapid Transit Company (IRT), opened on Oct. 27, 1904. Its first day of service had more than 150,000 passengers, running from City Hall to 145th Street. The fare was fixed at five cents, an affordable method of transportation for the city’s working class. In the early years, the IRT and other systems that emerged together to become known as the Brooklyn-Manhattan Transit (BMT) system funded a massive expansion dubbed the Dual Contracts, doubling the size of the network by 1913. In 1940, the IRT, BMT, and the Independent Subway System (IND) were unified under public control, simplifying fares and operations, which resulted in 2 billion trips annually by the 1950s.

The ’70s and ’80s were dark decades for the subway. Underfunding, poor maintenance, and rising crime impacted ridership to record the lowest rates, which made the M.T.A. launch a $54 billion capital program to improve infrastructure by 1981, including replacing the old tracks and rolling stock. In 1993, the MetroCard was launched, a switch to modernization for both subway and bus systems, and in 2000, more major investments were made to gain public trust, which led us to today. Comprising 472 stations, the subway serves about 5 million weekday riders, about 68% of New Yorkers. Its ongoing rollout of OMNY contactless payments and accessibility upgrades is proof of its commitment to modernizing its network. However, challenges still exist, including old infrastructure, delays, and declining ridership in a post-COVID world that still needs improvements and consistent investments.

Taxis: From Hackney Carriages to Uber Dominance

New York City's taxi industry has been an essential component of the city's transportation system since the mid-19th century, when horse-drawn hackney carriages first traveled the cobblestone streets. These early carriages were used as a luxurious service on demand for wealthier residents by charging passengers for rides between locations. The New York Taxicab Company appointed gasoline taxis in 1907, with 600 painted bright red and green. Motorized cabs gained popularity because they were a faster and more reliable option in comparison with horse-drawn alternatives. By 1910, over 1,000 gasoline-powered cabs flooded the streets of NYC, paving the way for the modernized industry seen today. In the 1920s, Hertz Rent-A-Car founder John Hertz debuted the iconic yellow taxi that we know today. The yellow color was selected because a 1960s study concluded it was the most visible color from a far distance, allowing passengers to identify taxis easily in the thriving streets of Manhattan. By the 1930s, taxis were a familiar sight on New York City's streets, providing cheap, convenient rides for a growing population. The medallion system was introduced in 1937 to regulate how many cabs could operate in the streets and to guarantee a certain level of service. The system limited the number of medallions to 13,595, a figure that remained constant for decades. Although this policy increased accountability and system stability, it blocked potential players, new drivers, and organizations from entering the industry. By the mid-20th century, medallion ownership had become a significant investment with values surpassing $1 million. By the early 2010s, Uber and other ride-hailing services were upending the taxi industry, shaking its dominance and reshaping the transportation market. Uber's app-based platform debuted in 2011 with upfront prices, shorter wait times, and convenient fares. Within a year, ride-hailing services began to appear, with Lyft also taking a significant market share. In 2018, NYC advanced a cap on growth, aiming to decrease the number of ride-hailing vehicles on the streets to stop oversaturation. The city launched congestion pricing zones in Manhattan to ease traffic flow and balance the competition between taxis and ride-hailing services. But the medallion system, which had always been stable and served as a symbol of the taxi industry, crashed. Medallion values hit rock bottom, leaving many owners bankrupt and their investments worthless. By 2019, the effect of ride-hailing was indisputable. In NYC alone, Uber recorded 91 million trips, while yellow cabs took just 77 million trips. In recent years, the focus has shifted to sustainability and accessibility. New York City, in 2022, started a pilot program to replace older taxis with electric models, aiming to electrify a third of the taxis by 2030. Still, challenges remain since the current system doesn't prioritize the needs of wheelchair-accessible vehicles (WAVs) and disabled passengers. While yellow cabs are an iconic symbol of New York City, their continued relevance in the face of changing consumer preferences and technology is a question mark. Ensuring that taxis are not just a prominent mode in the city's multimodal transportation future will require further digitized platforms, sustainable vehicles, and regulations focused on equity.

From subways breaking down barriers of surface congestion and enabling mass transit easily across the city, buses improving access to underserved neighborhoods, and taxis providing on-demand service, each mode of transportation has had a unique impact on the city's growth, boosting tourism and supporting the economy. They together represent not only technological progression but also NYC's capacity to adjust to the needs of an ever-evolving city. This evolution allows us to see in what measure different transportation modes influence each other.

3.2 Key Boroughs of New York City: Economic and Cultural Centers

The city's transportation system is thus a lifeline for its residents. There are several high-density populated areas located in New York, which serve as the focal point for a lot of the economic and cultural activities of the city. Areas such as Downtown Brooklyn, Flushing Queens, Midtown Manhattan, and Bronx Grand Concourse are some of these key areas, which cluster a lot of the city's economic and cultural activities. Let us investigate some of the key characteristics of the 5 boroughs of New York City.

Manhattan: It is the financial and cultural heart of the city. During the day, it has the highest population density in the world because of its accumulation of businesses and cultural attractions. Iconic neighborhoods like Midtown Manhattan and the Financial District are served by key transportation hubs such as Grand Terminal Station and the Port Authority Bus Terminal.

Brooklyn: Once a center for docks and factories, it has rapidly gentrified at the turn of this century into one of New York's most iconic and influential areas. Between 2010 and 2015, it has seen the greatest number of jobs being added compared to any of the boroughs outside Manhattan, adding 106,000 jobs. Its location serves to be a key area for the city's transportation network, as it connects the residential areas of Long Island with Manhattan via bridges, tunnels, and the subway.

Queens: It is the most ethnically diverse borough of the city, having some of the highest numbers of foreign-born residents, accounting for 47% of its population. It serves as a major residential zone in the city, having key population clusters such as Flushing and Jamaica. It also hosts the two main airports of New York: La Guardia and JFK Airport.

Bronx: It is a traditionally underserved region of New York, largely being a residential hub for the relatively poor population of the city. It is located very close to Manhattan, thereby making it a key source of labor for the city's economy. It also faces some of the highest commuting times of any of the boroughs in the city. The Metro-North commuter rail serves as the major transportation lifeline for its residents.

Staten Island: It is the least densely populated area of the city, characterized by its suburban setting and relative disconnection from the rest of the city. Often referred to as the 'forgotten borough' of the city, it has the highest rates of car ownership in the city, which is highlighted by the limited public transportation options available. The Staten Island Ferry serves as a major link to its residents, connecting them to Manhattan, whereas the Verrazano-Narrows Bridge provides the crucial roadway linkage to Brooklyn.

3.3 Pricing models and Regulations

Yellow Taxis and the Medallion System

To ensure accuracy, historically, taxi fares were calculated using mechanical or electronic taximeters calibrated periodically, with prices based on time and distance. Consequently, operational costs—fuel prices, maintenance, and inflation—led to occasional fare adjustments. This is why fixed meter rates were often revised annually or in response to economic changes. This system was created to control the number of taxis on city streets, ensuring service quality, driver income stability, and market predictability. The medallion became a tradable commodity, its value fluctuating with market demand and TLC policies. Yellow taxis primarily operate in Manhattan and nearby areas, where street-hail demand is highest. They are equipped with meters that calculate fares based on time and distance, with additional surcharges for specific conditions:

- **Peak Hours:** An extra fee applies during weekday rush hours.
- **Congestion Surcharge:** A flat fee of $2.50 is levied for trips below 96th Street in Manhattan, introduced in 2019 to alleviate traffic and support public transit funding.

Despite their dominance, yellow taxis have faced criticism for limited coverage outside central Manhattan and for their rigidity in responding to real-time fluctuations in demand.

Introduction of Green Taxis (Boro Taxis)

In response to the geographic service disparity, TLC introduced green taxis, also known as Street Hail Liveries (SHLs), in 2013. These vehicles were designed to address the transportation needs of NYC's underserved outer boroughs (Brooklyn, Queens, Staten Island, and the Bronx) and northern Manhattan. Unlike yellow taxis, green taxis are prohibited from picking up street hails in Manhattan's central business district and at city airports, except through pre-arranged rides.

Green taxis operate under the same regulated pricing model as yellow taxis, with fares determined by meters based on time and distance. The introduction of green taxis marked an important step in addressing the transportation inequities in NYC, providing more accessible and affordable options for residents in low-demand areas.

Operational and Regulatory Distinctions

The distinction between yellow and green taxis extends beyond geography to operational and market dynamics:

- **Street Hail Zones:** Yellow taxis have exclusive rights to street hails in central Manhattan, while green taxis serve outer boroughs.
- **Meter-Based Pricing:** Both services share the same regulated pricing structure, but green taxis rarely encounter high-density zones with congestion surcharges.
- **Licensing and Oversight:** Both are regulated by the TLC, ensuring driver and passenger safety, service quality, and fare transparency.

While both services follow traditional meter-based pricing, the geographic segmentation reflects an attempt to balance demand across the city, mitigating the dominance of yellow taxis in high-traffic areas while extending service to underserved regions.

The Emergence of For-Hire Vehicles (FHVs) and Ride-Hailing Platforms

The for-hire vehicle (FHV) sector has long complemented NYC's taxi system, traditionally serving pre-arranged trips through livery cars and black cars. These vehicles cater to passengers seeking more personalized service than standard street-hail taxis, particularly in outer boroughs and less-trafficked areas. However, the early 2010s ushered in a transformative era with the rise of app-based ride-hailing platforms like Uber and Lyft, fundamentally altering urban mobility dynamics.

Unlike traditional taxis, FHVs operate using app-based algorithms to calculate fares dynamically based on factors such as real-time demand, traffic conditions, and driver availability. This shift introduced innovative features like upfront fare estimation, GPS-based route optimization, and cashless payments, providing a seamless experience for passengers. Additionally, ride-hailing platforms diversified service offerings, including premium options like Uber Black and shared rides, expanding accessibility across different income levels and travel preferences.

4. Methodology and Findings

This thesis employs a multidisciplinary methodology combining descriptive analysis, modeling techniques, and comparative methods to explore urban mobility patterns and fare elasticity across various transportation modes. The methods were selected to address different facets of the research, ranging from analyzing spatial and temporal trends to quantifying the impacts of operational and contextual factors on urban transportation systems.

Descriptive Analysis

Descriptive methods served as the foundation for analyzing and visualizing trends across datasets, offering insights into spatial, temporal, and demographic patterns relevant to transportation systems. These methods were applied universally across all research components to provide a coherent understanding of the underlying data.

Temporal analyses involved exploring trends in trip volume, duration, and distance across different times of the day and week. Line graphs and histograms highlighted variations in user behavior, peak usage times, and operational dynamics. Spatial patterns were analyzed using geospatial mapping techniques, which visualized the distribution of trips across pickup and drop-off zones, emphasizing regional differences in service utilization.

While these methods were broadly applied, some descriptive techniques were tailored to specific analyses. For example, demographic and geographic factors were integrated into the analysis using supplementary datasets, such as census data and public transportation accessibility measures. Population density and transit accessibility metrics were spatially matched to transportation data, providing additional context for understanding demand and supply distributions across urban areas.

Modeling Techniques

Statistical and computational models were employed to quantify relationships between variables and assess transportation dynamics. These models offered insights into factors driving demand, pricing, and mobility patterns across multiple modes of urban transit.

Ordinary Least Squares (OLS) Regression

OLS regression was a common tool applied across multiple research components to identify the factors influencing trip characteristics and fares. Common independent variables included trip distance, duration, traffic conditions, temporal indicators (e.g., weekends and rush hours), and location-based attributes. These models established baseline relationships, allowing for comparisons between modes such as buses, ride-hailing services, and traditional taxis.

Fixed Effects Models

To account for unobserved heterogeneity in spatial and operational characteristics, fixed-effects (FE) models were utilized. These models incorporated fixed effects for locations, such as pickup or drop-off zones, to control for location-specific influences while isolating the impact of demand factors like congestion and time of day. FE models were particularly useful in identifying how urban density and geographic variations shaped pricing and demand responsiveness across transportation systems.

Cluster-Based Analyses

K-means clustering was used to segment locations into categories based on shared characteristics, such as urban density or transit accessibility. This approach provided a more granular understanding of transportation patterns by grouping zones into clusters, such as high-density pickup to low-density drop-off areas, allowing for detailed insights into fare and demand variations across different urban contexts.

Advanced Modeling Approaches

In parts of the thesis requiring predictions or analysis of sequential data, machine learning models were applied. Long Short-Term Memory (LSTM) networks captured temporal dependencies in hourly and daily demand trends, while Gradient Boosting techniques uncovered non-linear relationships among operational and contextual factors. These advanced models complemented traditional methods, offering a more comprehensive understanding of transportation dynamics.

Comparative Methods

Comparative analyses were integral to understanding differences between transportation modes and their operational frameworks. Descriptive statistics compared attributes such as trip distances, durations, and fares across modes, providing insights into user behavior and service efficiency. Statistical significance tests, including t-tests and Mann-Whitney U tests, were applied to identify meaningful differences in observed trends.

Geospatial comparisons further explored regional disparities in service usage. Maps illustrating the dominance of specific transportation modes in different zones revealed spatial variations in accessibility and demand. For example, some analyses focused on relative concentrations of public transit versus taxis to identify gaps in service coverage or to assess the complementarity of modes.

The methodology was designed to address a range of research questions across individual parts while maintaining coherence in the overall analysis. Descriptive methods provided a foundation for exploring trends and patterns, while regression and clustering techniques quantified relationships and identified nuanced differences between modes. Advanced models enhanced the depth of analysis, offering insights into temporal dynamics and complex interactions. Together, these approaches provided a holistic view of urban mobility, capturing both the shared and distinct characteristics of fixed and dynamic pricing systems.

5. Introduction to Individual Parts

In this research, a mix of predictive modeling, geospatial analysis, and qualitative methods have been employed: LSTM networks and Gradient Boosting to uncover temporal patterns, fare trends, and feature interactions. Geospatial analysis mapped demand density, accessibility, and transit gaps across boroughs. Comparative studies evaluated operational and pricing differences between taxis, ride-hailing services, and public transit. Public transit impacts were analyzed through correlations with shifts in taxi and ride-hailing usage. Additionally, socioeconomic factors and policies were integrated to contextualize findings, such as fare caps and congestion pricing, along with weather conditions and traffic, which further enriched the analysis, providing actionable insights on cost efficiency and accessibility.

The analysis begins by examining mobility trends in NYC's outer boroughs following the introduction of enhanced taxi coverage, such as the Green Taxi program. This research addresses the question of whether these measures have effectively improved transportation equity by increasing access to reliable taxi services in historically underserved areas and how these changes have influenced broader mobility patterns.

Next, the relationship between NYC's public bus system and taxi usage is explored, with a focus on understanding the interplay between these modes of transportation. By analyzing fluctuations in taxi demand relative to bus service enhancements and operational changes, this section seeks to uncover whether improved public transit services can alleviate taxi dependency or whether they coexist in a complementary fashion.

Building on this, the variability in costs between comparable Green and Yellow taxi rides is studied over time, addressing questions about fare consistency and the factors driving price differences between these two services. This analysis showcased how difficult it is, for comparable matching rides, to study the variability of fares over time, and how, in order to obtain a fare cost difference prediction, it is better to rely not just on geospatial data but on other complementary elements as well.

The next part investigates trip purposes and usage patterns, comparing Green Taxi users with ride-hailing service users such as Uber and Lyft. This section explores the distinct user behaviors and preferences that shape demand for these services, answering questions about how spatial, temporal, and demographic factors influence trip purposes and usage frequency.

Finally, the analysis turns to pricing models, focusing on the comparison between fixed pricing (used by traditional taxis) and dynamic pricing (employed by ride-hailing platforms). By investigating fare sensitivity to demand-driven factors such as traffic and weekends, this section addresses how pricing mechanisms impact urban mobility and service accessibility.

6. Individual work By Param Sumiran: Mobility Trends in New York City's Outer Boroughs Post Enhanced Taxi Coverage.

6.1 Introduction

New York City's (NYC) taxi services have always been centered around lower and midtown Manhattan. As such, the boroughs of Brooklyn, Queens, Bronx, Staten Island, and Upper Manhattan faced unequal availability of taxis. To fix this issue, the city of New York decided to introduce Green Taxis in 2013. These special classes of taxis are only allowed to pick up customers in Brooklyn, Queens, Upper Manhattan, Bronx, and Staten Island.

Around the same time the city planners were introducing the Green Taxi, another massive revolution was happening in the transportation and tech industry. Uber was founded in 2009 in San Francisco and began operations in NYC by the year 2011. Uber is termed a creative disruptor in the transportation industry (Willis and Tranos, 2020) owing to its rapid expansion in cities all over the world and the ease with which it put traditional street-hailing taxis out of business.

At the turn of this decade, the people of NYC, particularly the outer boroughs, had enhanced taxi coverage. They had a variety of options available to them, such as Uber and Green Taxis, along with other tech-based taxi services such as Lyft, which also began operations in NYC in the year 2014. The rise in taxi services must be viewed in the context of NYC transportation landscape where 76% of all neighborhoods rely on extensive Subway and Bus network (Kaufman et al., 2014). However, the NYC subway, in recent years, has degraded in terms of the quality of service it offers to the people; the stations are not being maintained properly, line disruptions are becoming frequent, and metro cars have become a hotspot for crimes such as robberies and murders (Moore and Sedacca 2024).

Given the ongoing changes that have been happening in the transportation ecosystem, we want to see the travel patterns and mobility choices of the people of NYC. Being a vast city with diverse neighborhoods that have different levels of income, centers of employment, and availability of resources, NYC shows notable localized trends and patterns that usually get overlooked. This paper aims to answer some key questions regarding the trends of mobility in geo-specific areas of New York.

- Does Enhanced taxi coverage lead to a reduction in the usage of Subway?
- Does enhanced taxi coverage lead to more congestion?
- Has the introduction of Green Taxi been impactful?

Such a geo-specific analysis will be of relevance to city planners as it pinpoints transportation and mobility issues unique to each city segment, consequently enabling the development of targeted solutions and enhancing governing efficiency.

6.2 Literature Review

Geo-Specific Trends

The transportation network of a city plays a vital role in the economic and social welfare of its people. It allows for the people to access jobs of their choice by extending the total number of jobs available to them. Businesses usually tend to agglomerate into clusters to facilitate transfer of resources and workers easily thereby increasing productivity (Centre for Cities 2016). New York City has multiple centers of employment located, but the main center is the Central Business District of Manhattan which accounted for nearly half the jobs being created between 2010 and 2014 (56%). Along with Manhattan we are also seeing prominent centers of employment propping up in Western Queens and Northern Brooklyn ("Employment Patterns in NYC" 2016).

A vast transportation network also facilitates a booming real estate industry in the city because people need not stay near centers of employment and choose to live in places away from their work, allowing for house prices to soar in other areas. A study conducted in Santiago; Chile saw apartment prices soar up by 9% wherever a metro line was introduced (López-Morales et al. 2023). For the city to garner maximum benefit of employment agglomeration an effective and vast transportation network is vital.

The study conducted by NYU Rudin Center of Transportation (Kaufman et al. 2014) categorized the city of New York into 3 distinct segments of job accessibility: High, Medium, and Low based on the amount of time it takes to reach centers of employment within 60 minutes on a Monday morning using only public transit. The analysis presented a substantial variation in the levels of transit access throughout the city. However, it was found that people living in the middle segment, i.e. areas which have somewhat sufficient access to public transit, had the lowest median income compared to the higher and lower neighborhoods, this being an unexpected result as access to public transit is directly correlated with job accessibility and higher levels of income (Centre for Cities 2016). This anomaly can be explained by the fact that affluent people tend to live outside the city with minimal public transit options and commute to work via Private Cars: 52% of people in the lowest segment of the neighborhoods use private cars for their daily commutes (Kaufman et al. 2014). The middle segment of neighborhoods would then appear to be best suited to pivot from public transit usage to taxi usage considering they do not have the income and means to buy a car to fix for the mediocre public transit network being available to them. The introduction of enhanced taxi coverage must have had a considerable impact on the usage of public transit in these neighborhoods.

Uber vs Green Taxi

Traditional taxi services in most cities have a significant disadvantage when compared with tech-based taxi hailing services such as Uber. Street hailing services such as the Yellow and Green Taxi in NYC are heavily regulated, and the number of taxis allowed to function in the market is controlled via the medallion system (Willis and Tranos 2020). This proves to be of a massive advantage to services such as Uber and Lyft, which allows anybody with a car to become a driver and anyone with a phone to be a customer. The disruption caused by services such as Uber and Lyft can be felt in most cities all over the world. A study conducted in Taiwan showed that Uber caused an 18% decrease in traditional taxi revenue in just its 3rd year of operations (Chang 2017). Another study conducted in Los Angeles saw that Ride Hailing Companies such as Uber significantly decrease traditional taxi ridership. The study also found that Uber and other tech-based services have a complimentary effect on Public Transit usage, i.e. customers usually use Uber and Metro together to get around the city (Contreras and Paz 2017) and not as a substitute for either method. While this may be the case in LA, researcher found that the opposite to be true in Chengdu, China which saw Tech based taxi service DiDi proving to be a substitute for Public Transit consisting of Subways and Buses, wherein 33.3% of all public transit trips were substituted with DiDi taxis rides (Kong, Zhang, and Zhao 2020). The relation between different modes of transportation varies depending on the internal dynamics of each city. In NYC, we are seeing research that show Uber absolutely decimating traditional taxi services. A study conducted between 2014 and 2015, saw that Uber was growing at a staggering rate in the Outer Boroughs of New York City, seeing a 550% overall growth in the city, with Brooklyn, Queens and Bronx showing a 528%, 1216% and 530% growth rate respectively (Correa 2024). These trends indicate that Tech based taxi services are moving towards putting the newly introduced green taxis out of business. As to the relation taxis have with public transit in NYC, research indicates that people choose their travel options based on multiple factors that include, wait-time, cost of fare, comfort, and accessibility. Taxis are primarily used more often during off-hours (late nights and early mornings) and social periods (Saturday and Sunday) (Ulak, Yazici, and Aljarrah 2020), however it is important to note that this study was limited to lower Manhattan and did not assess the relation taxis have with subways in the outer boroughs of NYC. We are seeing a rapid degradation in Subway service quality with rising wait times, delays, and line disruptions (LaFrance 2017). This is also accompanied with a rise in violent crimes within the Subway system of NYC. This would certainly reduce the propensity of people to choose Subway as a method of transportation to get around the city. There are solid research foundations that show Tech Based taxi Services such as Uber, are proving to be detrimental to the business of traditional taxis in NYC. While it is generally accepted that Uber and Lyft are replacing green taxis in the outer boroughs, there is a lack of understanding about the effects these services are having on the Subway usage in outer boroughs.

Congestion and Private Car Usage

There are conflicting reports as to the effect that enhanced taxi coverage has on the traffic congestion in a city. One study conducted in China found that as ride-sharing companies increased activity in the city, the Air Quality Index of the city worsened, implying that the number of vehicles increased on road (Wang et al. 2022). As mentioned in the previous section tech-based taxi services acted as complimentary modes of transportation along with Subways and buses in LA, thereby reducing the reliance on private cars. One of the key reasons taxi and public transit can act as complimentary services and not substitutes is when the city has poor public transit network as is the case with LA (Yukana 2021), the people choose to combine different methods of transportation to get around the city. This finding is corroborated by another study conducted for the whole of United States, which saw that taxis and public transit can act as complimentary modes of mobility while reducing carbon emissions as less people choose to travel by single occupant car (Zhang and Zhang 2018). Enhanced taxi coverage also has a significant effect on the usage of private cars, a study conducted in Cape Town, found that the entry of tech-based taxi services reduced the number of private cars being on the road, allowing for the upper-income people of Cape Town, those who have access to private cars, to give up using their cars and switch to taxis. NYC on the other hand is known to have one of the most extensive networks of public transportation, even with such an extensive network of public transit, NYC is facing massive issues with congestion, so much so that the city authorities are planning to introduce a congestion toll on every vehicle that enters Manhattan's Central Business District (Kramer, Devlin, and Houlis 2024). A study conducted by PFNYC found that congestion in NYC costs the city about $9.17 Billion in delayed commuting hours, with Brooklyn and Queens accounting for the highest number of lost hours in traffic outside of Manhattan. They also found that traffic increased by 53% over the entire metro of NYC between the years 2006 and 2018 (PFNYC. 2020). Private car ownership has also been rising in the city, as per the data procured from the US Census, NYC (excluding Staten Island) saw a 12% rise in private car ownership between 2012 and 2021, with the Bronx and Brooklyn contributing 22% and 13.2% respectively. The rise of congestion in NYC can be an effect of the enhanced taxi coverage being introduced in the city. This could also highlight the failure of the public transit system in the city, as more people are switching to private cars or taxis as a method to get around the city. The next section of this paper will discuss the data sources and the processing of that data to understand the trends of transportation in NYC.

6.3 Data Processing

Data Sources

The primary sources of Data for our analysis are:

1. NYU Rudin Centre Neighborhood Job Accessibility Data
2. MTA Subway Station Geom Data
3. US Modified Zip Code Tabulation Data
4. MTA Subway Usage Data (2013-2022)
5. TLC Green Taxi Data
6. NYC Taxi Zones Data
7. NYC Open Data Automatic Traffic Volume Counts Data

Data Description

1. NYU Rudin Centre Neighborhood Job Accessibility Data: This dataset is the result of a study conducted by NYU, which categorizes the neighborhoods of NYC into 3 separate bins (Upper, Middle, Lower) based on the amount of time it takes to reach centers of employment by using public transit only. Jobs were considered accessible only if they could be reached within 60 minutes on a Monday morning. Key columns for our analysis include:
    - Neighborhood - Names of the neighborhood based upon the US Zip Code Tabulation Area (ZCTA)
    - Rank - The ranking of each neighborhood based on how accessible jobs are

- Borough - Borough Name
- Zip - Zip Code for the neighborhood.

2. MTA Subway Station Geom: This dataset taken from NYC Open Data consists of all the subway station names located in NYC along with their geometric coordinates. Key Columns for our analysis include:
    - Stop Name - Name of the Subway Station
    - Geo-reference - Longitude and Latitude for the Subway Station

3. US Modified Zip Code Tabulation Data: This dataset taken from NYC Open Data consists of the neighborhood names present in NYC along with their Zip codes. Also present in this is the Geometric coordinates of each of those neighborhoods. Key columns for our analysis include:

- MODZCTA: Zip code for each Neighborhood of NYC
- Geom: Longitude and Latitude for each Zip Code area

4. MTA Subway Usage Data 2013 -2022: This dataset taken from the Metropolitan Transport Authority (MTA) consists of the number of riders for each station in NYC within the time; 2013-2022. The method to calculate ridership as specified by the MTA, consists of counting the total number of passengers who enter a subway station, excluding the employees and passenger transfers. Key Columns for our analysis include:

    - Station Name
    - Borough

- Years

5. TLC Green Taxi Data: The dataset taken from the Taxi and Limousine Corporation (TLC) of NYC, includes key metrics on the green taxi usage in NYC, such as Pickup Datetime, Dropoff Datetime, Pick up ID, Drop off ID, along with other information such as fare amount, trip distance etc. Each row in this dataset, signifies a trip record, thereby giving us the total amount of ridership. There are 3 datasets corresponding to green taxi usage, each for the years 2017, 2018 and 2019 respectively. Key Columns for our analysis include:
    - PULocationID - The taxi zone area, in which the passenger was picked up.
    - DOLocationID- The taxi zone area, in which the passenger was dropped off.

6. NYC Taxi Zones Data: TLC has divided NYC into several taxi zones for easy categorization taxi trips, each zone as a corresponding location ID. This Dataset was taken from NYC Open Data. Key columns for our analysis include:
    - Zone name
    - ID
    - Geom

7. NYC Open Data Automatic Traffic Volume Counts Data: This Dataset, taken from NYC Open Data consists of automated traffic volume counts, that measure the volume of traffic at bridge crossings and roadways all over NYC. A key limitation of this Data is that the frequency with which it measures traffic volume count is quite irregular for each year, thereby giving us a skewed understanding of the actual traffic volume of the city. Key columns for our analysis include:

Year - The year of count

Vol - Total Sum of count within a 15-minute interval

Geom - Geographic coordinate of the location where the count was taken.

Data Processing

Subway Data Integration

1. The Subway usage data with the column *Station Name* and MTA Subway Geom Data also having the column *Station Name* were normalized so that they could be of the same format and then merged, thereby creating an intermediary dataset with the Subway Usage Data for each Subway Station and their Geographic coordinates.
2. The NYU Rudin Data consisting of *Zip Code* numbers and the Zip code Tabulation Data also consisting of *Zip Code* numbers were normalized and merged. The intermediary dataset formed here consisted of Neighborhood names and their corresponding geographic coordinates.
3. Finally, the intermediary datasets created in steps **1** and **2** were merged using the *Haversine formula* $(a=sin2(2\Delta\phi)+cos(\phi 1)\cdot cos(\phi 2)\cdot sin2(2\Delta\lambda))$* *(The Shortest distance between 2 points)* where each Subway Station was assigned to a neighborhood in the city based on the centroid of that neighborhood.

The resultant dataset formed consisted of all the Subway stations and their corresponding location in the respective neighborhood taken from the NYU study as shown in Fig.1

Figure 1. Subway Stations within NTA Zones

Green Taxi Data Integration

1. The NYC city taxi zone data with the Neighborhood Data formed in **Step 2** of the previous section is based on the common geographic coordinates (*Geom Column*). This was done using the Geopandas library of Python. Thereby creating an intermediary dataset of neighborhood names and rankings and their corresponding taxi Zones. It is important to note that since the Taxi zones are relatively bigger than the size of a neighborhood based on the Zip code Tabulation, multiple neighborhoods fall into the same Zone.
2. This intermediary data was then merged with the TLC Green Taxi data on the common column of Location ID. Thereby creating a dataset consisting of the taxi usage data, which zones they correspond to, geographic coordinates, neighborhood names, and rankings.
3. The data was cleaned and sorted, and any statistically insignificant entry such as taxi

travel time being less than 1 minute or trip distance being less than 0.1 miles were excluded. We only considered the years 2017-2019 as the Covid pandemic of 2020 skewed any data from the years 2020-2022.

The resultant dataset shows us the trends of green taxis in each neighborhood segment based on the NYU segmentation. Fig. 2 is the map of the neighborhood segmentation.

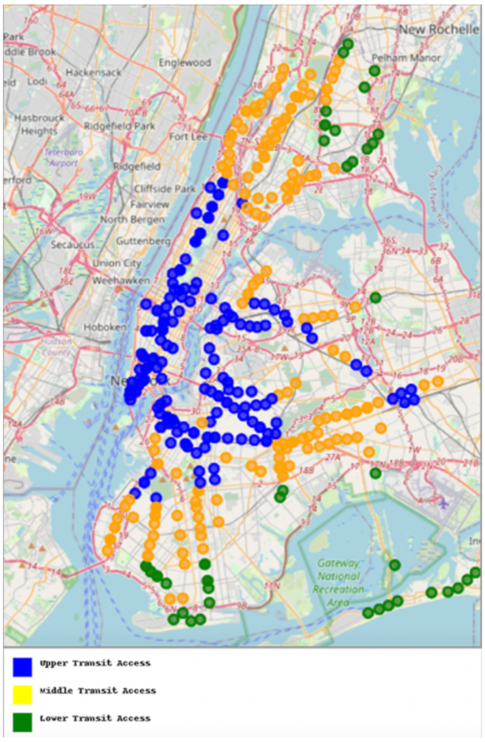

Figure 2. Neighborhood Segregated by Rank

Congestion Data

The dataset Automated Traffic Volume Counts has irregular frequency of Data counted, per location per year. This inconsistency can skew the understanding of the traffic volume patterns for the boroughs. To mitigate this problem, we have normalized the data by dividing the total volume counted per borough per year by the frequency of observation per borough per year (Total Volume/Total Observation). This normalized data gives us a better and more accurate picture of the traffic volume present in the city of NYC over the years. It is important to acknowledge that the randomness with which the data is collected means that data is not entirely accurate even after normalization. Nevertheless, it does provide us with a reliable approximation into the traffic situation of NYC.

Observations Count by Year and Borough (2013-2019):

	Yr	Boro	Observations
0	2013	Bronx	26417
1	2013	Brooklyn	23926
2	2013	Manhattan	41919
3	2013	Queens	29717
4	2014	Bronx	29961
5	2014	Brooklyn	21864
6	2014	Manhattan	29169
7	2014	Queens	45556
8	2015	Bronx	29123
9	2015	Brooklyn	20845
10	2015	Manhattan	13218
11	2015	Queens	55071
12	2016	Bronx	22368
13	2016	Brooklyn	46113
14	2016	Manhattan	11569
15	2016	Queens	35307
16	2017	Bronx	33315
17	2017	Brooklyn	31462
18	2017	Manhattan	29460
19	2017	Queens	23928
20	2018	Bronx	13136
21	2018	Brooklyn	19542
22	2018	Manhattan	23705
23	2018	Queens	38894
24	2019	Bronx	7680
25	2019	Brooklyn	35157
26	2019	Manhattan	13714
27	2019	Queens	49781

Figure 3. Explains the number of observations per borough through the years (2013-2019)

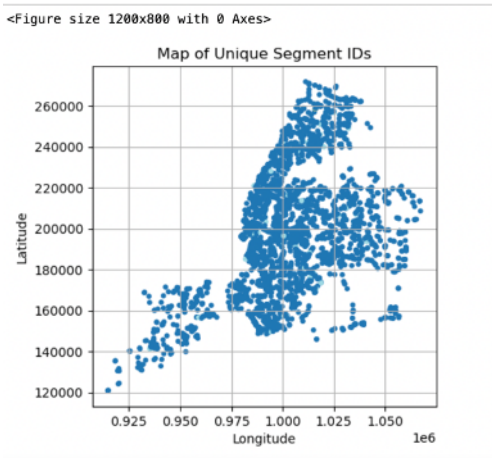

Figure 4. Explains the locations of the points where each count was taken.

6.4 Result and Discussion

Following our comprehensive discussion regarding the theoretical framework to analyze the geo-specific patterns of mobility in NYC, we also emphasized the significant changes that have been happening to the transportation ecosystem over the past few years. Having presented a detailed account of our data processing methodology, this following section presents the findings of our analysis, wherein we discuss the Geo-Specific Subway trends, Green Taxi Trends and Congestion Trends for the city of New York.

Subway Trends

Having grouped the Subway stations of NYC into the 3 ranked categories, Fig.5 shows us the frequency of subway stations located in each segment across the boroughs. Manhattan has the highest frequency with most of the stations belonging in the High rank category which was expected considering it is the economic and cultural center of Manhattan. An interesting thing to note is that the Middle Third neighborhoods have subway stations in every borough of NYC, with most of them being centered around Brooklyn.

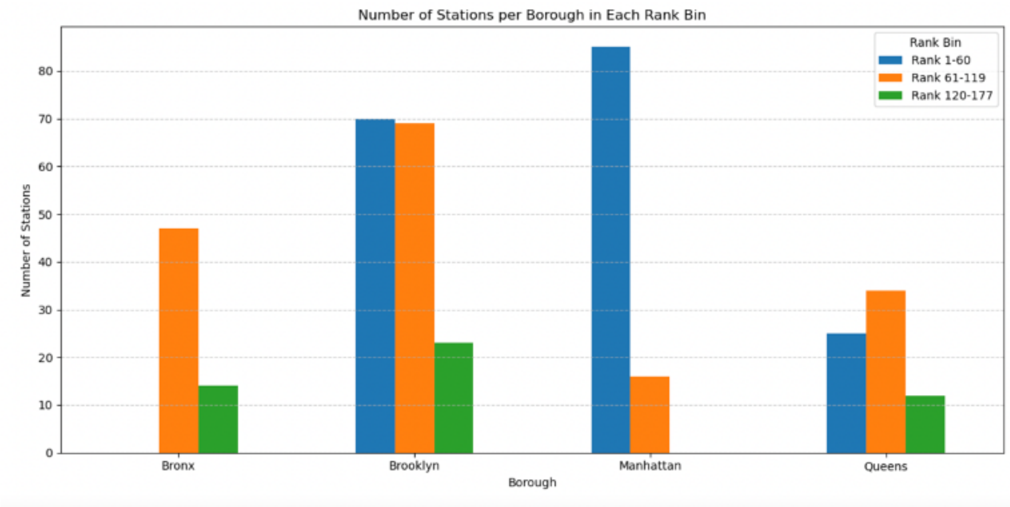

Figure 5. Frequency of Subway Stations by Borough

Brooklyn and Queens are key boroughs it seems regarding Subway transportation as it contains subway stations belonging to each of 3 the rank segments implying that certain parts of these boroughs are very well connected while other parts aren’t as well served. Bronx only contains those neighborhoods that belong to Middle or Low-ranked neighborhoods telling us that it is a moderately served region of NYC, with some parts of it being very poorly served.

Fig.6 contains 2 graphs showing us the ridership trends for each of the ranked neighborhoods and for each of the boroughs. It is clear and expected from this graph that the High ranked neighborhoods and Manhattan are seeing a rapid rise in Subway usage implying that the advent of enhanced taxi coverage has had little effect on the usage of Subway here. The people of this neighborhood still use Subways as their primary method of transportation, with the trends indicating more and more people every year are using Subways. Subway usage has fallen in the Middle-ranked Neighborhood which is mirrored with the fall in Subway Usage in Brooklyn and Queens. This tells us that enhanced taxi coverage must have had a substantial effect on the usage of the Subway in these areas of NYC. The low-ranked neighborhoods which mainly consist of the Bronx, have not had much of a change in subway ridership which can be explained by the over-reliance on private car usage in these areas of NYC.

Fig.7 is a heatmap of the stations with the most ridership in NYC. As we can see the subway system of NYC is primarily centered around Lower and Midtown Manhattan with additional subway hotspots being in Flushing's Brooklyn and Southern Queens. This tells us how the subway system of NYC is so disproportionately distributed, primarily around the high-income neighborhoods of NYC. Our analysis shows us that Subway usage is on the rise among the high-income groups of NYC, while the middle-income neighborhoods are seeing a sharp fall in the usage of Subways, as seen in Fig.8

In summary our analysis reveals a declining trend in subway usage among the residents of the Outer Boroughs of the city, primarily Brooklyn and Queens while the people living around Manhattan are increasingly depending on the Subway. Fig.9 shows us the exact percentage changes in Subway usage among the 3 categories of neighborhoods and their corresponding changes across the boroughs.

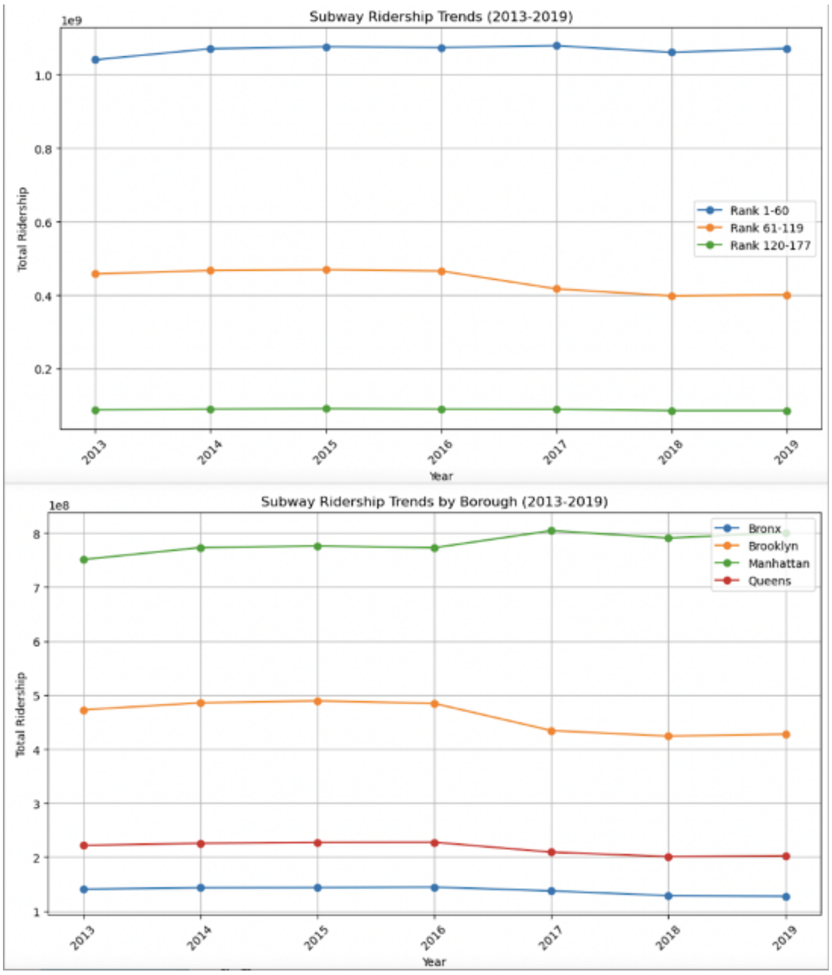

Figure 6. Geo- Specific Ridership Trends

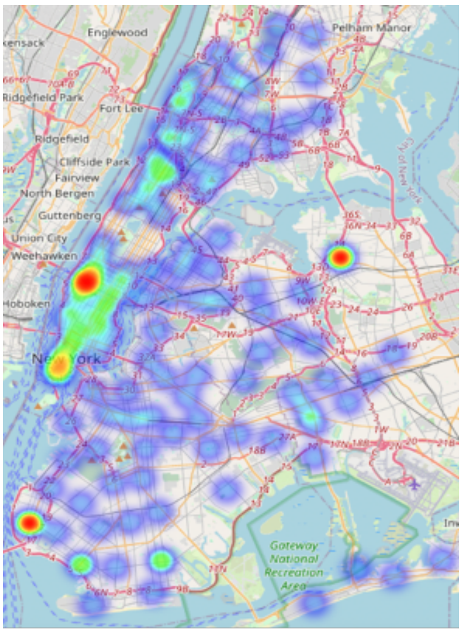

Figure 7. Heatmap of Subway Ridership by Area

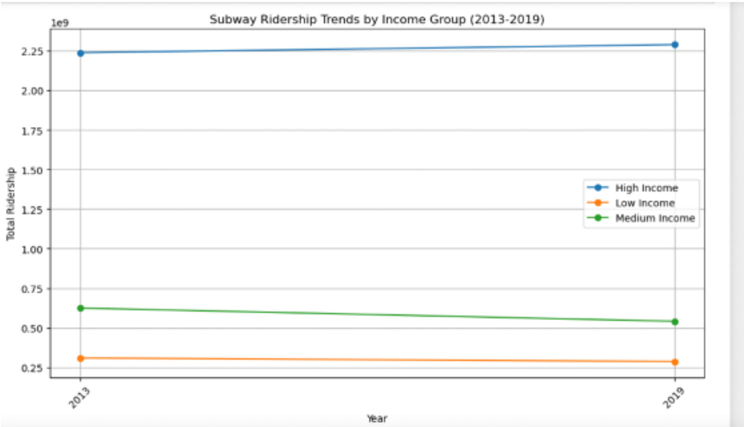

Figure 8. Subway Ridership by Income Group

```
Change in ridership for Rank 1-60: 2.97%
Change in ridership for Rank 61-119: -12.38%
Change in ridership for Rank 120-177: -2.24%
```

	Borough	Percentage Change (2013-2019)
0	Manhattan	6.616199
1	Bronx	-9.242982
2	Brooklyn	-9.548400
3	Queens	-8.710048

Figure 9. Geo-Specific Percentage Change in Subway Ridership

Green Taxi Trends

Our geo-specific analysis of the Green Taxi data provided us with some intriguing insights into how the residents of the 3 ranked categories have been utilizing Green Taxi over the past few years. Fig.10 highlights some of the key descriptive statistics about Green Taxi travel patterns from 2017 to 2019. It is clear from this data, that the people living in the High-rank neighborhoods rely on and use Green taxis more frequently than the people living in the Middle or Lower neighborhoods, as per the data the usage of Green taxis in the High ranked neighborhoods is 50.27% higher over a 3 year average than the Middle ranked neighborhoods. An interesting point to note is that the Middle-Ranked Neighborhoods have the highest population, yet they rank only 2nd in green taxi usage. In contrast, the population of the Low-rank neighborhoods is quite comparable to the High-rank neighborhoods, yet the Green Taxi usage is disproportionally lower:1800% lesser over a 3-year average. The population and descriptive statistics of the 3 ranked neighborhoods are highlighted in Fig.11. This highlights how ineffective Green Taxis have been in the Lower and Middle ranked neighborhoods of NYC, wherein they have not been able to serve the people as effectively as they should have.

According to Fig.12 Green Taxi usage in Geo-Specific areas of NYC has been declining rapidly between our analysis period of 2017 to 2019. The highest reduction is seen in the Upper-ranked neighborhoods with a 60% drop, followed by Middle ranked neighborhoods with a 58% drop and a 29% reduction in Lower ranked neighborhoods. These significant decreases highlight the failure of Green Taxis in serving its intended customers of the residents of the outer boroughs of NYC.

2017

	Total Trips	Average Trip Distance	Average Trip Fare
Rank 1-60	5946990.0	2.653355	11.642676
Rank 61-119	3816118.0	2.788523	11.865482
Rank 120-177	214694.0	3.871980	15.195868

2018

	Total Trips	Average Trip Distance	Average Trip Fare
Rank 1-60	4131998.0	2.818462	12.263921
Rank 61-119	2873025.0	3.377934	13.868892
Rank 120-177	277315.0	6.126355	22.174079

2019

	Total Trips	Average Trip Distance	Average Trip Fare
Rank 1-60	2344948.0	2.717859	12.045640
Rank 61-119	1578868.0	3.278741	13.555426
Rank 120-177	152281.0	5.878741	21.543816

Figure 10. Descriptive Statistics on Green Taxi Ridership

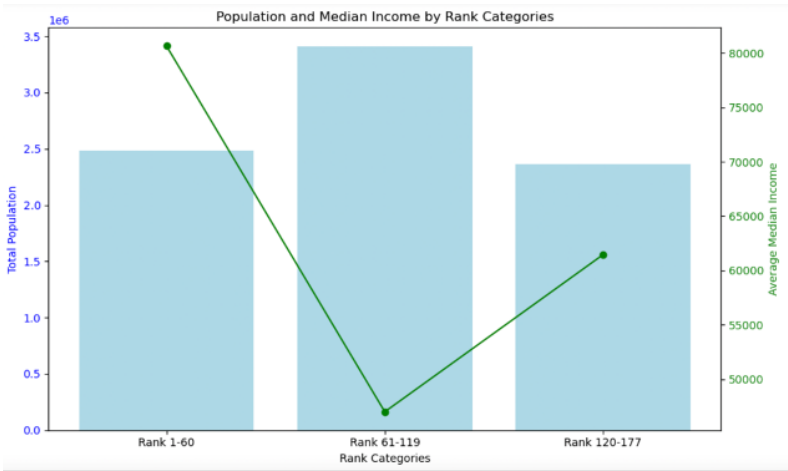

Figure 11. Geo-Specific Population and Median Income

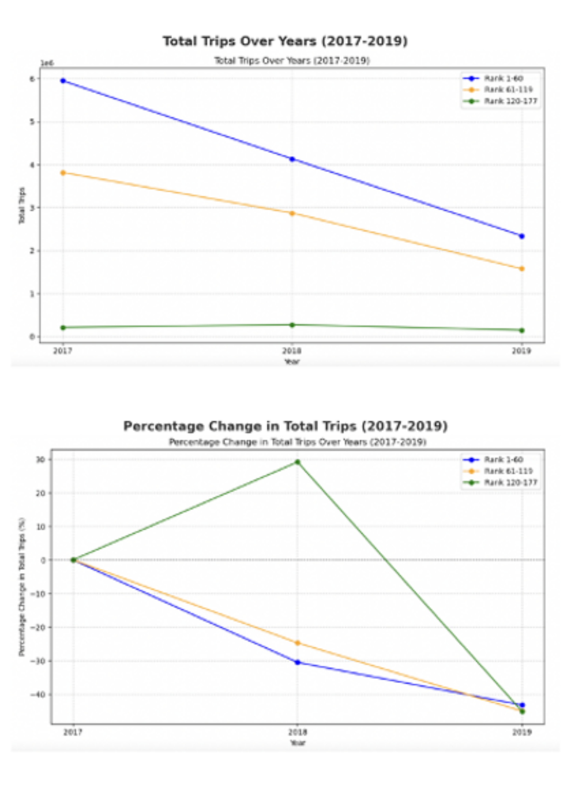

Figure 12. Geo-Specific Change in Green Taxi Ridership

Congestion Trends

Fig 13. Highlights the increase in Traffic congestion in NYC between the years 2016 and 2019, with the total normalized traffic volume increasing at a rate of 10.34% per year. Brooklyn and

Queens account for the highest rise in non-normalized traffic volume between the years 2013 to 2019, showcasing a 191% and 65% increase in traffic.

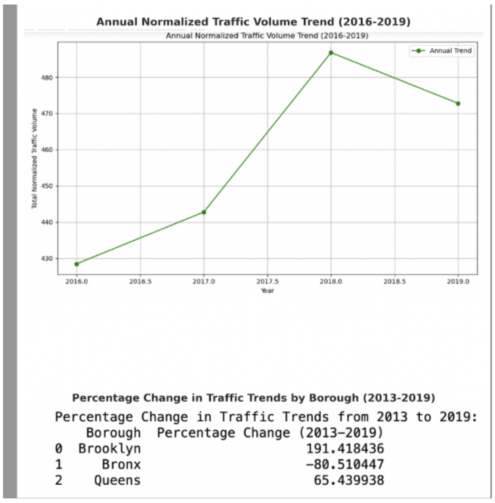

Figure 13. Geo-Specific Traffic Volume Trends

6.5 Limitations & Conclusion

Limitations

- This study has not analyzed the effect enhanced taxi coverage has had on the Metro North commuter rail service, which is a key transportation system playing the vital role of connecting the suburban population with the city. The inclusion of the Metro-North Rail data could provide further insights into the regional mobility patterns.
- Our study is primarily a data description study, which focuses on the recent trends of Mobility in NYC. Future research could investigate the causal relationships between Subways and Taxis. This would help determine in a more definite way whether these modes of transportation are complimentary or supplementary to each other.
- Further causal analysis can also be conducted to ascertain the relationship between Taxis and private car usage in NYC.

Conclusion

Over the years we are seeing contrasting trends emerge in the mobility patterns across the different neighborhoods of NYC. Subway usage has been rising rapidly in the Upper-ranked neighborhoods, consisting mainly of Manhattan and the Prime areas of Brooklyn and Queens. However, Subway usage has declined significantly in the Middle-ranked neighborhoods, consisting of Central Brooklyn and Queens. These areas account for the highest population among the neighborhood ranks. In the Low-ranked neighborhoods which include the Bronx and Upper Manhattan, Subway usage has remained stagnant, which is explained by the over-reliance on Private cars in these areas.

Green Taxi usage has been declining sharply across all areas of NYC, reflecting the limited success of the program. In the Outer boroughs tech-based taxi services such as Uber and Lyft have replaced the usage of Green Taxis (Correa 2024).

Meanwhile, congestion has been steadily rising across NYC, with Brooklyn and Queens showing some of the highest levels of Congestion outside of Manhattan. Private car ownership has also seen a rise in the city.

Although Public Transit remains the dominant mode of transportation in the city, our analysis showcases a trend wherein people are now shifting away from Subway usage and moving towards tech-based taxi services such as Uber and Lyft or relying on Private cars. These trends suggest that NYC outer boroughs, particularly areas of Brooklyn and Queens, historically known for their reliance on Public Transit are shifting towards a more car-dependent transportation culture.

To address the challenge of rising car dependency in NYC, city planners should focus on enhancing the existing public transit system, improving its quality of service, cleanliness, safety, and reliability ensuring it remains a viable option for commuters. The city should also invest in pedestrian infrastructure like walking and cycling paths to increase non-motorized travel options. City planners should also consider phasing out the Green Taxis as this initiative has been a failure and the presence of these taxis contributes towards congestion on the roads.

6.6 Resources

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