Examination of Taxi Travel Patterns in Arlington County

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ABSTRACT

This research focuses on utilizing typically overlooked taxi manifest data to analyze taxi operations with respect to transit, and also presents alternative uses for the data in transportation planning. Taxi travel characteristics are explored for Arlington, Virginia, a county containing both urban and suburban qualities. Previous research contends that manifest data can provide valuable quantitative descriptors of taxi travel. This thesis attempts to describe taxi travel by quantifying trip characteristics; the shortcomings of using manifest data are discussed and the results are reported. The taxi operations results are then compared for weekend and weekday travel and also for airport and non-airport bound travel. Several key differences between these groups of taxi trips are discussed.

Next, an investigation of the relationship between mass transit facilities and taxi travel is conducted. Since taxis provide a complementary, yet competing public transportation service to mass transit, it is hypothesized that examining the proximity to transit options and the timing of taxi trips can provide insight to the perceived gaps in mass transit services. However, the data show that simply examining geographic or temporal characteristics of taxi trips does not define clear relationships between transit facilities and taxi use. Instead, the results suggest that other variables, such as land use and vehicle access, may hold a greater influence over the generation of taxi trips.

Despite the difficulty in using manifest data to determine gaps in transit, the data collected by taxi regulators could have numerous applications for planners. Possible applications for the type of taxi data used in this research are explored and a potential data flow for agencies is proposed.

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List of Abbreviations

ART:	Arlington Regional Transit
BTS:	Bureau of Transportation Statistics (US DOT)
CBD:	Central Business District
DOE:	Department of Energy
DOT:	Department of Transportation
DRT:	Demand Responsive Transit
FTA:	Federal Transit Administration
GIS:	Geographic Information System
DCA:	Ronald Reagan National Airport Code
IAD:	Dulles International Airport Code
MARC:	Maryland Rail Commuter
MDT:	Mobile Data Terminal
NTD:	National Transit Database (Federal Transit Authority)
OD:	Origin-Destination
VRE:	Virginia Rail Express
WMATA:	Washington Area Metropolitan Transportation Authority

1. Introduction

Taxis are omnipresent in the urban transportation landscape. The for-hire service is older than most people realize, and more vital to the health of a city than many would think. Taxis provide a valuable service that helps bridge the gaps left by a mass transit system. The long history of the taxi industry brings with it significant strife and conflict. Labor disputes, unfair competitive practices, and systematic fraud have left imprints in the history of the taxi industry. As a result of this complicated past, the types of taxi regulations vary greatly by locality; some jurisdictions heavily regulate taxi companies while others have deregulated taxis altogether. In addition to the various regulatory approaches, the mechanisms of taxi ownership and operation may also vary from company to company. For example, some companies may lease the vehicles to the drivers for a fee while other companies provide support services and branding and allow drivers to own their vehicles. Add to these complexities the fact that many taxi companies also provide ancillary public transport functions in contract with public agencies, and the ability to analyze operations becomes murky at best.

1.1. Motivation

The goal of this thesis is to congregate the various spandrels of taxi research into a single case study examination. By quantifying the various aspects of taxi travel and how they relate to an area's transportation infrastructure, several planning applications could possibly be developed to advance the synergistic effect of taxis with mass transit systems. A major motivating factor for this thesis was that the amount of available taxi data is rapidly expanding as more and more systems develop improved data collection methods. It is important to begin exploring the various ways to examine this data to improve overall urban transport.

1.1.1. Hypotheses

1. Taxi trip rates and characteristics will demonstrate observable shifts as access and quality of transit service vary temporally and spatially.
    a. Gaps in local mass transit systems can be identified and the role of taxi travel in public transit can be more clearly defined using the available manifest data.
2. Weekend taxi trips will exhibit different characteristics than weekday trips, and airport taxi trips will differ from non-airport taxi trips.

Specifically this thesis will complete the following objectives:

- Compare Airport and Non-Airport Taxi Travel
- Compare Weekday and Weekend Taxi Travel
- Analyze Taxi Travel with respect to Transit Facilities and compare taxi efficiency to other transit modes
- Propose additional uses for taxi data in transportation planning

1.2. Overview

This thesis focuses on three main topics of discussion: taxi travel, relating mass transit to taxi, and planning applications for taxi data. A brief literature review outlines some of the pertinent research conducted in the field of taxi travel. An introduction to the geographic features of the area is presented to familiarize the reader with Arlington County. The characteristics of taxi travel in Arlington are presented with attention to operating efficiency. Next, taxi travel characteristics in relation to mass transit are explored. A discussion of possible planning applications for taxi data follows the results. Finally, areas for further research are identified and the conclusions of the research are provided in the last chapter.

2. Literature Review

The available research into taxi operations has been mainly on the aggregate level, but there is still a significant amount of relevant research available. Empirical data is often difficult for academia to access, since it is produced and maintained by private companies. In addition, much of the research involving taxi trips involves the study of the economics behind fare regulation and demand, but may not necessarily explore the taxi's relation to mass transit. Much of the more recent research tends to focus on Demand Responsive Transit services and using taxis in non-traditional roles.

2.1. Role of Taxi in Transport

The role of the taxi in public transportation has recently become more ambiguous as improvement in dispatch technology has created a large interest in the development of Flexible Transport Services (FTS). Thanks largely to emerging ITS products, transit services are nearing the ability to provide truly demand-responsive services[5]. Computer aided dispatching is also improving the efficiency of operations[14]. Several authors have explored the development of FTS in Europe, especially in the UK. Brake (2005) outlines some of the difficulties in developing DRT, including vehicle types, cooperation and coordination of different service providers, and cost.

The use of taxis in other areas of transit as substitutions for ambulances, school buses, or as a means of providing paratransit services for the elderly and disabled has gained popularity in many US cities[11]. Routinely, Arlington is mentioned in literature concerning the use of taxis for providing ADA paratransit services. A recent study by the National Cooperative Highway Research Program (NCHRP) found that taxis are being utilized in vastly varying capacities by different jurisdictions[11]. The authors of the study present several case studies in which taxis are used for paratransit for the elderly or disabled and cite Arlington's Red Top cab company as an example of a fleet embracing the use of wheelchair accessible taxicabs. A case study is also presented for Houston, Texas, in which taxis are used for non-emergency 911 responses instead of ambulances. The authors cite the drastic difference in cost in dispatching an ambulance ($1,750 per trip) compared to a taxi ($28 per trip)[11]. Another study highlights the use of taxis in ADA paratransit by Arlington as a method for cost savings[5].

Additionally, the use of taxis in rural public transportation is also supported by numerous studies for school transportation and other transit needs. The scattered demand patterns in rural areas require flexible services that are often difficult for larger scale transit systems to provide. Research into improving DRT has been especially intense in the United Kingdom where telematics have enabled DRT to expand its role rapidly[5]. However, Brake (2004) contend that there are many potential barriers facing DRT, including overlapping service providers and difficulties selecting the appropriate vehicles.

2.2. Applications of Taxi Data for Regulators

Technology has progressed greatly in the last fifteen years, especially in the areas of GPS technology and wireless communications. Unfortunately, taxi records are still maintained mainly through hand written records for regulators to review. Private companies may have a trove of electronic and GPS data, but may be unwilling or unable to share with local regulators. The data available include descriptors, such as waiting time, pickup and drop-off locations, and fare data. Cooper et al (2010) examine some of the potential benefits to taxi regulators and operators that manifest data can provide. The authors suggest that regulators utilize the data to make decisions that affect taxi operations and the public. For example, when deciding to grant an application for additional cabs, regulators could examine the wait time data provided by the company to decide if they actually require additional taxis to meet demand. Cooper et al (2010) also illustrate the usefulness in evaluating the often elusive concept of service equity by allowing for wait times in different geographic and demographic areas to be compared. The authors additionally recommend using the taxi data to check on the working hours of taxi drivers and ensure that they are not exceeding their allowed shifts[7]. These examples of uses are useful in examining taxi operations, but additional applications involving transit are also possible.

2.3. Modeling Taxi Travel

Taxi service modeling has improved significantly in the last decade. Kim et al (2010) summarize the difficulties in modeling taxis. The authors contend that the challenge to modeling taxis lies in the asymmetric demand as well as spatiotemporal variations in demand[10]. Kim et al (2010) propose an agent based model for simulation of taxi travel; unfortunately, models such as the one proposed by the authors usually rely on assumed passenger travel patterns or estimated OD data for validation.

Additionally, there have been several models used to forecast taxi demand. A popular multiple regression model has been proposed by Shaller (2005), but according to Cooper et al (2010), the model does not actually predict the demand for taxi service but rather the number of cabs required. In addition, Cooper et al (2010) suggest that using actual empirical data, such as that presented in this study, could provide useful results for developing and calibrating accurate demand models.

2.4. Expanding on Research

The literature mentioned in this section serve as an indication of the growing trend to attempt to utilize the ever present fleets of taxis for non-traditional purposes that could save agency and users costs. If taxis are to continue to expand in function, then the analysis of their operations should increase as well. Little has been done to show how using available taxi data can be used to support the critical decisions of how to customize the role of taxis in a specific urban setting. This thesis attempts to demonstrate that taxi services can be analyzed with respect to other transit operations using readily available manifest data. The benefits of the spatial representation of taxi trips are also emphasized, especially with regard to existing transit infrastructure. Finally, this thesis attempts to pull together all of the analyses into a discussion of possible alternative agency processing of taxi data.

3. Background

Before delving into the various results and research methods, it is helpful to provide information on several background topics to provide context for the results. This section will present a brief history of taxis followed by background information specific to Arlington County transportation and taxi operations.

3.1. History of the Taxi

Gilbert and Samuels chronicle the history of the taxicab in order to explain the evolution of regulatory practices, and also point to the divergence of mass transit from taxis in their earliest forms[9]. The first modern urban taxis were actually horse-drawn vehicles called "hackneys" that appeared in the European cities of Paris and London soon after the 1600s[9]. These hackneys dominated public transportation until technology eventually forced them out and they were replaced with automobiles.

The relationship between mass transit and taxicabs can be traced back to the emergence of the omnibus in Paris in the 1820s[9]. According to Gilbert and Samuels, a French businessman came up with the idea to operate larger vehicles that follow fixed routes and times[9]. These first mass transit operations directly competed with taxis in the open market, but both faced political obstacles. Mass transit continued to develop and grow over the next few decades, and eventually streetcars became the predominant force in urban areas in the US. After WWI, streetcars faced a challenge from a newer form of transportation known as jitneys. The jitneys drove ahead of the streetcars on their routes and picked up the passengers waiting for streetcars ahead of the streetcars. As a result, the streetcar owners petitioned for regulations that banned jitneys, and the pressure resulted in many anti-jitney laws, in American cities, which prohibited shared rides[9]. These new types of regulations sharply separated taxi services from mass transit. There are however, a few existing examples of remaining jitney services in the United States.

3.2. Geographic Context

Transportation in its most elemental form is moving people and goods from one location to another. Understanding the underlying geographic characteristics of a region can provide context for the discussion of a region's transportation system. A brief overview of the geography of the Arlington area and the existing transportation infrastructure is provided to familiarize the reader with a framework for understanding the results.

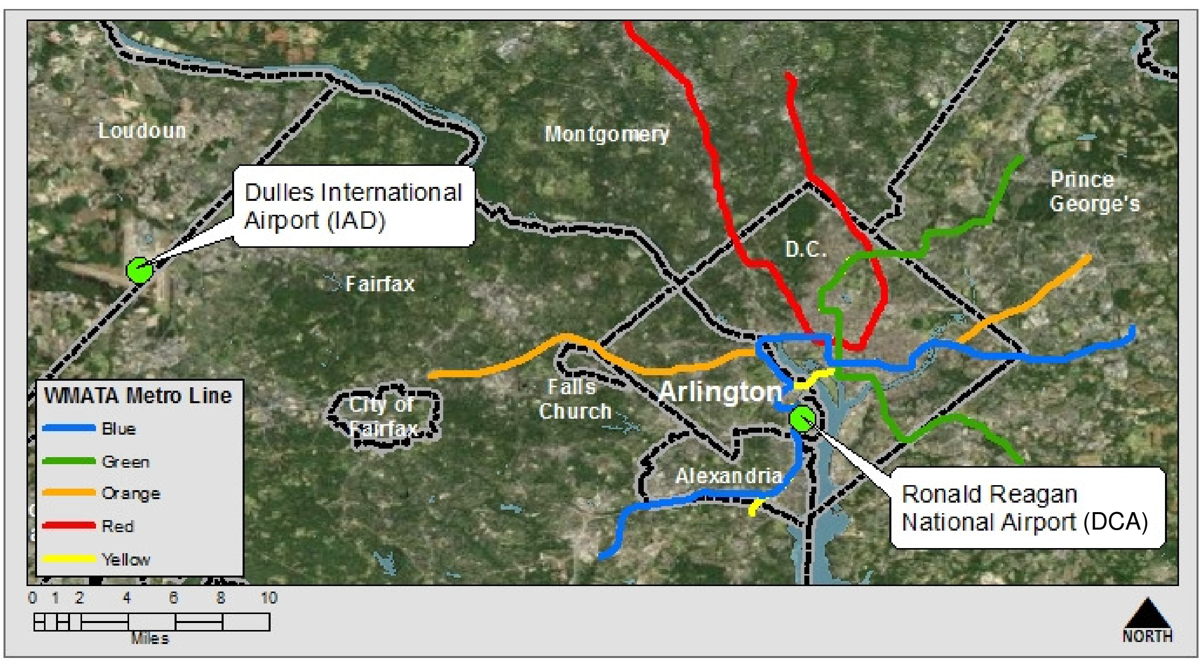
3.2.1. Study Area

Arlington County is located directly adjacent to Washington, DC across the Potomac River to the west. Although Arlington's taxi travel is the focus of this research, the taxi trips analyzed interact with the wider metropolitan Washington, DC area.

The County is the smallest by land area in the United States at only about 26 square miles, but has a significant population and tax base. According to 2010 Census data, there were approximately 212,000 jobs and 207,000 residents in 2010[3]. This suggests that Arlington serves not only as a suburb of Washington, DC, but also as a major employment center. Figure 1 depicts the geographic position of Arlington County in relation to Washington, DC as well as the locations of the Metrorail lines in Arlington. Metrorail is a heavy rail transit service provided by the Washington Metropolitan Area Transportation Authority (WMATA). It is an above-ground and underground system that follows the routes shown in Figure 1. Metrorail is probably the most recognizable transit system in the metropolitan area due to its reach throughout the District of Columbia, Virginia, and Maryland. Figure 1 also communicates the small size of Arlington County in comparison to the neighboring jurisdictions, such as Fairfax or Montgomery County. The majority of taxi travel occurred within the area shown in Figure 1, and taxi travel between neighboring jurisdictions was common.

3.2.2. Regional Airports

Washington, DC is served by two major airports: Ronald Reagan National Airport (DCA) and Dulles International Airport (IAD): both are high volume airports. DCA moved over 18 million passengers in 2010[13], while IAD moved more than 22 million passengers in 2010[19]. DCA is located in Arlington County and is therefore a major taxi trip attractor within the county. IAD is located in Sterling, VA about 40 minutes to the northwest of Arlington. At the time of this research, a Metrorail extension is being constructed to eventually connect to IAD, but the airport is currently accessible by car, taxi, bus, or a combination of bus and Metrorail. DCA is currently accessible by Metrorail on the Blue and Yellow lines as well as by bus and taxi.



SOURCE: Aerial imagery from Bing Maps base layer for ArcGIS

Figure 1 – Area Map

3.2.3. Existing Public Transportation Infrastructure

Arlington's existing public transportation infrastructure provides extensive services for its residents. There are rail, bus, and paratransit services within the County. The geographic configuration of the various transit modes is outlined in Figure 2 where the spatial relationship between the various taxi stands, metro stops, and bus routes is shown. The following section will briefly outline the various components of the transportation systems.

3.2.3.1. Transit Overview

The County contains two major Metrorail corridors along the Orange line from Rosslyn to Ballston, and along the Blue/Yellow lines from Crystal City to Pentagon City. The Metrorail ridership in Arlington was over 60 million in 2009[1], and serves as the dominant transit system in the County. The neighborhood areas referenced in the corridor descriptions are also displayed in Figure 2 for clarity. In addition to these high density districts, the Metrorail system also serves DCA and the Pentagon in Arlington County.

The County is served by both WMATA and Arlington Regional Transit (ART) bus systems. Figure 2 illustrates the geographic relationship between the WMATA routes and the ART routes. The WMATA bus service provides many routes along commuter paths and arterial roads. The ART routes serve as neighborhood collector routes that supplement the WMATA routes and connect residential neighborhoods to the Metrorail stations. The ART routes also supplement North-South travel within the County to connect the numerous East-West corridors. Although ART and WMATA bus services operate within the same areas, their functions are fundamentally different and therefore are not redundant.

In addition to bus and rail services, Arlington also provides paratransit services for elderly or disabled residents. The paratransit services offered by Arlington's program are fixed route and shared ride services that seek to "provide a comparable level of transportation as provided by ART, Metrobus, and Metrorail". To supply these services, the County uses WMATA's paratransit service Metro Access and also contracts with local taxi companies. Recently, the support for using taxis more prominently in paratransit has gained strength throughout major cities in the US. This hints that localities have begun to recognize the economic efficiency of using taxis in an expanded role.

Arlington has also championed transit use through active public relations campaigns and commuter services. The high number of roads with prominent bicycle and pedestrian facilities also encourages alternative modes of transportation.

Figure 2 shows the majority of the taxi stands are located within the Metrorail corridors with a few outlying stands at the Virginia Hospital Center and along Columbia Pike. Columbia Pike is a four-lane, east-west arterial route and also a major developed residential and commercial corridor. The area is also the targeted service area for a future streetcar system. Together, the transit modes and taxi services provide a comprehensive network of options for residents. In addition, the flexibility that taxis can offer in providing additional services makes it a valuable asset to the transportation system. It is this utility that makes understanding taxi travel so critical to improving transportation systems.

3.2.4. Existing Land Use Patterns & Impact on Taxi Operations

Land use has a large impact on the local transportation operations and the overall day-to-day qualities of the residents' lives. Population density in Arlington County is concentrated along the two major metro corridors on the Orange line from Rosslyn to Ballston and on the Blue line from Pentagon City to Crystal City. These two corridors contain a majority of Arlington's commercial and residential activities due to their higher density. It follows then that the taxi operations should be most concentrated in these areas.

The use of taxis in these areas is encouraged by certain land use characteristics. For example, many residential high-rise apartment buildings have designated phones that are tied directly to the taxi dispatchers to allow for easy contact between residents and taxis. The Crystal City area contains a large number of hotels due to its proximity to the airport. As a result, there are numerous taxi stands in the area, and many trips between hotels in the area and the airport are provided by the taxi companies each day. The remainder of Arlington to the north and south of the Metrorail corridors is largely composed of single-family residential areas with significantly less density. This mix of high density Central Business District (CBD) areas with typical suburban characteristics gives Arlington County a unique blend of land uses that requires mixed transportation strategies.

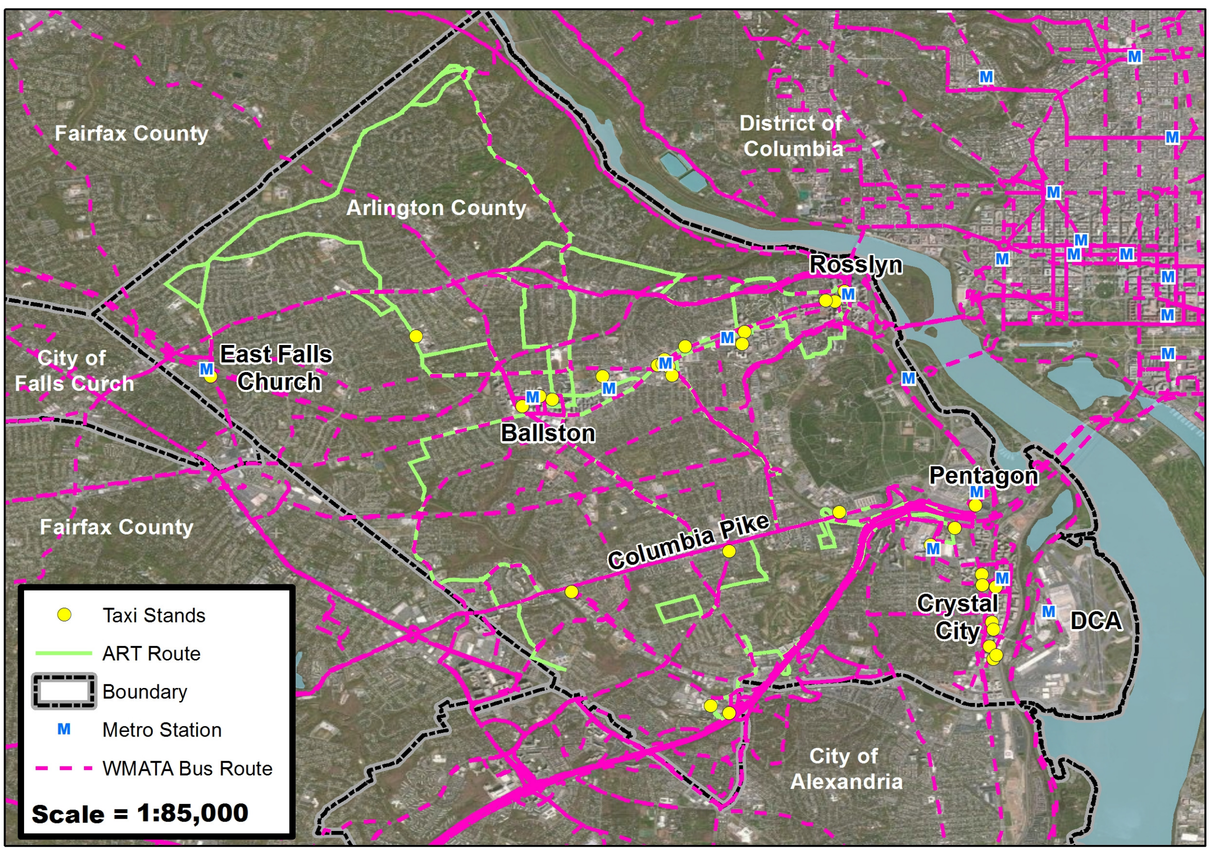


Figure 2 – Public Transportation Options in Arlington County, VA

3.3. Existing Taxi Operations in Arlington

The existing taxi operations in Arlington are governed by the regulations outlined in the county ordinance. Although the regulations include traditional controls, such as fare regulation, Arlington also imposes progressive regulations, such as fuel economy requirements and credit card acceptance for all taxis[4]. The following section will briefly outline the regulatory and economic environment, under which taxis operated in Arlington during the research data timeframe.

3.3.1. Operational Regulations

The current regulations for taxicabs licensed in Arlington County follow a structure similar to the neighboring jurisdictions of Fairfax County, the City of Alexandria, and the District of Columbia. The entry to the market is controlled by the County Board in the form of operating licenses. At the time the data used in this research was collected, there were approximately 765 taxis licensed to operate in Arlington, 666 of which were part of companies that provided dispatch service[1]. The taxi regulations require one part of the trip—either the origin or the destination—to be within the County limits. A few of the key additional regulations are further discussed in the following sections.

3.3.2. Fare Regulation

Arlington has regulated taxi fares in a manner similar to its neighboring jurisdictions. Fare structure proves relevant regarding airport surcharges and baggage handling fees. The additional charges for airport taxi access hint at the differences between traveling to the airport versus other taxi trips that will be discussed later in the thesis. The following list summarizes the system of fare regulation outlined in the County Ordinance[4] and is paraphrased from the Arlington County website[18]:

- *For the first one-sixth (1/6) mile (initial drop charge): two dollars and seventy-five cents ($2.75)*
- *For each succeeding one-sixth (1/6) mile or fraction thereof (mileage charge): thirty-five cents ($0.35)*
- *For each fifty-six (56) seconds of wait time: thirty-five cents ($0.35)*
- *For each additional Passenger twelve (12) years of age and older when more than one (1) Passenger is transported: one dollar ($1.00)*
- *For each suitcase (in excess of two (2)), if handled by the Driver: fifty cents ($0.50)*
- *For each footlocker or similar-size case handled by the Driver: two dollars ($2.00)*
- *Tolls paid by the Driver between the point of Passenger pickup and the Passenger destination will be added to the Passenger's fare, provided that the Passenger is first informed by the Driver of the existence of a toll, and further provided that the Driver first gives the Passenger the option of the Taxicab taking an alternative route, which route would not require the payment of a toll.*
- *Provided that the Passenger is first informed by the Driver of the existence of an airport surcharge, where the Driver pays such surcharge, the surcharge will be added to the total fare.*

The fare structures must provide a balance between affordable service and a profitable industry. For this reason, fare increases are usually favored by the taxi companies and opposed by the public. Often, determining the structure and amount of taxi fares is one of the most challenging tasks for regulators. They must weigh the interests of multiple groups, while also allowing for rates that are competitive with neighboring jurisdictions. Fare regulation is a topic that receives a good deal of attention in multiple disciplines of academia from urban planning to economics and sociology. This paper does not focus on the fare structure except as a reference for the relative cost of trips.

3.3.3. Fuel Economy Requirements

Arlington adopted a minimum fuel efficiency requirement for all new or replacement cabs. The ordinance outlines increasingly stringent requirements from 2010 through 2021. Although these regulations do not apply to cabs already in service, the ordinance specifies the maximum life of a cab. This means that once a taxi reaches the end of its useful life it must be replaced with a vehicle meeting the current fuel efficiency requirements.

At the time the data used in this paper were collected, the fuel efficiency standards had not yet gone into effect. However, by the end of 2010, 22% of the total fleet was composed of hybrid vehicles[1]. This suggests that the introduction of hybrid vehicles had begun earlier in the year, probably during the time that the data was collected for this study. This paper will not evaluate the impact of the hybrid vehicles on operating efficiency, since there were not data available that identified which specific taxis were hybrids. Subsequently, however, this leads to a vital caveat in analyzing taxi efficiency; although taxis can be evaluated from a passenger-mile efficiency standpoint, the true environmental impact should take into account the efficiency of the fleet vehicles as well.

3.3.4. Jurisdictional Regulations

The Washington, DC metropolitan area contains a wide array of jurisdictional boundaries. Not only is the region split between the state level governments of Maryland, the District of Columbia (not a state, but similar in structure), and Virginia, but it also traverses multiple counties and cities as well. Because taxi regulations within each jurisdiction are different, the potential for violations is high, and regulations that protect local interests are often conflicting with regional mobility. For example, for taxi trips provided by Arlington cabs, the origin or destination of each trip must be within the county limits. This policy is meant to prevent Arlington cabs from cruising in other jurisdictions, and vice versa. These types of regulations may impact the efficiency of taxi transportation in a regional sense, but they also provide a means of combating over-supply of taxis in congested areas.

The effects of the differing jurisdictional regulations can be seen on the user level. For example, taxis licensed in DC may reject a fare to Arlington (from DC) simply because the fare structure for them does not make the trip profitable because there is no guarantee of a return trip. However, an Arlington cab may journey into DC to a dispatched fare because its fare structure makes the trip profitable. Because of the drop off and pickup location rules, the DCA airport in Arlington provides a major boost to its taxi operations. Arlington taxis are able to pick up fares to DCA from Maryland, DC, and other counties. Airport fares are especially attractive to the Arlington taxis because once they drop off a passenger at the airport, they are immediately available for hire in their jurisdiction. On the other hand, all taxi trips from IAD are exclusively serviced by the Washington Flyer company, although any company can drop a passenger off. It should be noted that DCA is serviced by multiple taxi providers—not just Arlington cabs.

3.3.5. Taxi Stands

Arlington provides several taxi stands on public streets as shown in Figure 2. They are geographically distributed throughout the County to match the land use patterns. There are taxicab stands at every Metrorail station in Arlington to provide connectivity and accessibility for Metrorail riders. In addition, a taxi stand is provided near the Virginia Hospital Center. The hospital location is essential because some of the taxis are contracted to provide rides for seniors or the disabled who may need transportation to non-urgent medical care. Finally, there are a few locations where the taxi stands are only operated during certain times of the day. This is true especially in the Rosslyn-Ballston corridor where there is a large volume nighttime activity. These time dependent stands operate as parking spaces for the majority of the day and taxi stands for the rest of the day depending on the restrictions determined.

3.3.6. Taxi Travel Trends at the Time of Sampling

Towards the end of 2010, a County Board report examined the application for more licenses by a select few taxi companies. The report demonstrated that the level of taxi travel had declined over the previous few years while the use of transit had risen. In addition, the report outlined declining taxi travel indicators and suggested that population and job growth had been outpaced by the number of new cabs in the previous years[1].

3.4. Background Summary

The Washington metropolitan area creates a myriad of transportation challenges. The heavy federal presence in the city creates a large employment center that demands a high level of mobility to function. Arlington's position adjacent to the downtown DC area combined with large employment centers within the County itself creates a mixture of commuter and business related travel demand. To provide mobility and reduce congestion, the County relies on a mixture of transportation strategies. The taxi's role in these strategies is critical—providing a supplement to mass transit and connecting users without personal vehicles.

Taxi services in Arlington are regulated by a variety of statutes—most of which are typical of many major urban areas. The primary goal of taxi service in the County was to use taxis to connect users to transit hubs and stations. To accomplish this, stands were placed at major transit hubs and activity centers. Finally, although the taxi travel demand may have been faltering in 2010 compared to previous years, the taxi's ability to adapt had led to a significant amount of ADA paratransit trips through County contracts.

4. Methodology

The research focused on using empirical data from daily driver manifests. The manipulation and analysis of the data is described in the following section. The process used is important because in practice, many jurisdictions that regulate taxis have the same or even more robust raw data available to them. By utilizing the approach outlined, planners and engineers could tap into a readily available data source to identify possible service improvements in mass transit systems and taxi services.

4.1. Data Collection

The data were compiled from driver logs submitted to Arlington for regulatory purposes. Arlington granted access to the manifests with the understanding that the results and digitized data would be shared once the research was complete. The manifests represent those collected for the largest three taxi companies in Arlington that provided dispatch services. The manifests theoretically contained both dispatched and hailed trips according to the taxi companies, but the actual number of included hailed trips may be higher than those included on the manifests. The Arlington ordinance requires that drivers maintain records for <u>all</u> trips, but enforcing this requirement is difficult and costly.

Since the three companies sampled make up the vast majority of the total fleet, the results generated were considered to be representative of the entire fleet. Each manifest included, among other information, the following parameters for <u>each trip</u> provided by the taxi:

- Trip Origin Address
- Trip Destination Address
- Pick-up and Drop-off Times
- Number of Passengers
- Fare

In addition to the individual trip data, each daily manifest contained, among other information, the following summary data (totals for each date):

- total fare
- net mileage (odometer)
- paid miles
- number of trips

The efficiency calculations are primarily based on the summary data, whereas the geographical and mass transit analyses were based on the detailed trip data. Although the volume of available data was large, the quality was not high. To utilize the data, an aggressive sampling plan was developed.

4.1.1. Sampling Plan

The manifests were hand written, which resulted in a significant portion being indecipherable and therefore unusable. As a result, the sampling procedure developed was aggressive. The available manifests spanned one week in April of 2010. For this research a weekday (Wednesday, April 28, 2010) and a Saturday (April 24, 2010) were chosen for in-depth analysis. These two samples were meant to represent weekday and weekend travel respectively. Every manifest from the chosen dates was either entered or cataloged as unusable. In this manner, a representative sample was compiled.

In addition to the detailed trip data, the daily summary data were compiled for every available manifest; the summary data was compiled for almost every manifest because the summary data was legible for virtually all of the provided manifests even if the trip data was unusable. In this way, aggregate data related to taxicab efficiency was compiled as a complement to the detailed trip data discussed previously. The daily summaries were often useable even if the individual trip data was not, because the summary data was more carefully tabulated and reported in general.

4.1.2. Manifest Quality

The information regarding trips provided by the taxi companies contained a significant portion of error. Many of the manifests were unusable due to various reasons. These reasons ranged from missing data categories to illegible handwriting. In addition, several manifests were missing because a portion of the total fleet was not in service on the days sampled or because the manifest for the selected date was unavailable (for instance if the driver did not return to the garage for a few days). Although the unavailability of a manifest does not degrade the quality of the sample taken, faulty manifests do. However, as demonstrated in Figure 3, the number of manifests successfully compiled represents a significant portion of the available Wednesday and Saturday manifests.

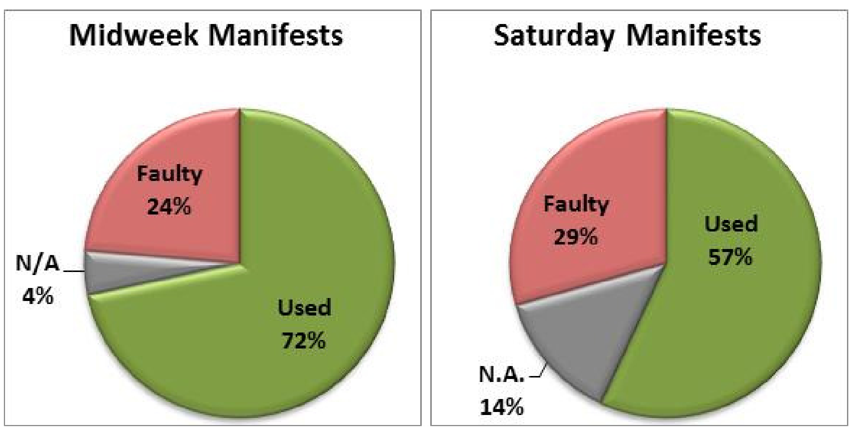


Figure 3 - Manifest Data Quality

Although the number of useable manifests represents a more than adequate portion of the total trips provided, the fact remains that these manifests were manually completed by various drivers. This characteristic introduces a certain amount of error into any analysis that uses the manifest data, and cannot be considered as accurate as electronically stored data.

4.2. Geographic Analysis

Upon compiling the raw data into an electronic format, the various trip locations needed to be referenced to a coordinate system for further geospatial analyses. The addresses for the trip origins and destinations were geocoded using ArcGIS Online Streets service.

This service was found to produce acceptable results based on sample destinations fed through the service. However, the geocoding process did result in a portion of unknown or un-located addresses. These addresses were either manually corrected using a variety of logical techniques or removed from the dataset if there was no address that resembled the entry. The main cause of un-located addresses was that the town or city information was incorrect. Because this data was rarely included on the manifests, the geocoding correction process relied extensively on the knowledge of local streets and naming conventions.

Following the geocoding of the addresses, several analyses were performed to evaluate the most likely trip path, length, and duration. Although the exact routes chosen for each trip are unknown, the paths of the taxi trips were estimated based on the shortest travel times using the US Streetmaps Data. The actual paths taken by the taxis are assumed to be similar enough to the calculated paths to allow for analysis. In addition, several statistics regarding the proximity of the trip locations to mass transit stops were calculated. The location of the origins and destinations to nearby mass transit stops were calculated based on the shortest distance, assuming that the facilities would be accessed by a pedestrian or bicyclist. Because of this, the routing routine was set to avoid limited access roads and toll roads (usually highways not accessible to pedestrians). Because the street network used to determine trip proximity to transit stops did not contain bike trails or paths, access by bicycle may have been underestimated in some cases.

4.3. Calculating Efficiency

Efficiency is evaluated in this thesis for various modes using two different measures. The first efficiency measure was the vehicle utilization percentage, μ_v; the vehicle utilization factor represents the ratio of the total passenger miles to the total vehicle-seat-miles. The calculation used the total recorded vehicle mileage (including out of service trips). This measure is basically an average system occupancy rate.

The second measure calculated was a ratio of total passenger miles to total fuel consumption. This measure uses the vehicles' energy consumption for each mode in addition to the occupancy, to create a valid basis for determining energy efficiency. The processes used to calculate both measures are discussed in the following sections.

4.3.1. Calculation of the Vehicle Utilization Factor

To calculate the vehicle utilization factor, μ_v, the total paid miles for each cab operating throughout the week of analysis were tabulated and compared to the total odometer miles recorded for the same date. Next, an average occupancy was determined using the detailed trip data collected for the two sample dates, representing an average weekday and weekend day. Friday tends to exhibit both weekday and weekend characteristics, so an average of weekday and weekend occupancy rates was applied. The occupancy estimates were then used to calculate the passenger miles provided for taxi service. Equation 1 summarizes the calculation method for the vehicle utilization factor for taxis, while Equation 2 presents the simplified version for transit using publicly available data from the National Transit Database.

Equation 1 – Calculation of Vehicle Utilization Factor for Taxis

$$\mu_{Vtaxi} = \frac{\left(\left(\frac{\sum_{i=1}^{T} P}{T}\right) * \frac{\sum M_P}{n}\right)}{\left(c * \frac{\sum (M_T)}{n}\right)}$$

Where:

μ_{vtaxi}	=	efficiency (ratio) of passenger miles to total seat miles
P	=	number of passengers for Trip i
T	=	total number of trips
M_P	=	paid miles per day
M_T	=	total odometer miles recorded
n	=	number of daily records used
c	=	capacity of the vehicle (assumed to be 4 for taxis)

Equation 2 - Vehicle Utilization Factor for Transit

$$\mu_{Vtransit} = \frac{M_P}{(c * M_T)}$$

Where:

$\mu_{vtransit}$	=	efficiency (ratio) of passenger miles to total seat miles
M_p	=	passenger-miles
c	=	vehicle capacity
M_T	=	total vehicle-miles

The data used for determining the taxi variables come from the summary statistics provided on each daily manifest. Since the manifests were manually recorded, this introduces sources of error in the computations. However, the results derived from the manifests closely resemble numbers published in a report by Nelson & Nygaard that examined Arlington taxi data in 2005[2]. This suggests that the data are reasonable for analytical purposes.

In estimating the total seat miles for the various transit modes several assumptions were made regarding the vehicle capacities of Metrorail, WMATA bus, and ART bus. The capacity of a Metrorail vehicle was calculated as 120 seats per car multiplied by an estimated 6 cars per train[20]. The WMATA bus capacity was conservatively assumed to be 65 passengers based on published data regarding the fleet[21]. The ART bus capacity was estimated as ten passengers less than WMATA based on the fact that the ART bus service operates a higher percentage of several smaller buses in their fleet[15]. Although these are only estimates of the average vehicle occupancy, the estimations should provide a basis by which to compare taxi vehicle utilization rate.

4.3.2. Calculation of Energy Efficiency

Evaluating the energy consumption of different modes of transportation is difficult because of the widely varying formats of available data. For example, Metrorail consumes electric energy while buses run on diesel fuel, compressed natural gas, and even bio-diesel. In addition, each mode has different vehicles and capacities. Fortunately, the National Transit Database (NTD) provides enough raw data to enable the wider comparisons. The available data included the annual passenger-miles as well as the energy consumption for each mode. To enable similar units, the energy conversions included in Table 1 were used to convert the various fuel forms to Gallons of Gasoline Equivalent or GGE.

Table 1 - Energy Content of Various Fuels[23]

	Gasoline	No. 2 Diesel	Compressed Natural Gas (CNG)	Electricity
Energy Contained in Various Alternative Fuels as Compared to One Gallon of Gasoline	100%	1 gallon of diesel has 113% of the energy of one gallon of gasoline.	5.66 pounds or 126.67 cu. ft. of CNG has 100% of the energy of one gallon of gasoline. [3]	33.70 kWh has 100% of the energy of one gallon of gasoline.

[3] Due to the infinite temperature and pressure combinations of gaseous fuels and their effect on fuel density, ft^3 units are not given. Most of these fuels are dispensed by Coriolis flow meters, which track fuel mass and report fuel dispensed on a "gallon of gasoline-equivalent" (GGE) basis.

SOURCE: Table generated using US DOE online alternative fuel comparison tool, http://www.afdc.energy.gov/afdc/fuels/properties.html

Taxi fuel consumption was estimated based on an estimated average fuel economy. The value of 26 miles per gallon was chosen from the Arlington ordinance fuel economy requirements. According to the Bureau of Transportation Statistics, the average new passenger car fuel economy has been greater than 26 mpg since 1985[24]. This suggests that 26 mpg is a conservative estimate for fuel consumption. In addition, a significant 22 percent of the Arlington fleet is comprised of hybrid vehicles[1], a fact that also points to the estimated fuel economy being conservative.

5. Taxi Travel Characteristics

After compiling the manifest trip entries, several patterns and characteristics of Arlington taxi travel began to emerge. Figure 4 and Figure 5 show the completed geocoding and routing process for the weekday and weekend taxi trips, respectively. The majority of destinations and origins are within Arlington and the Northwest DC area. Immediately noticeable is the similarity of the two maps. This suggests that the regional taxi travel patterns on the weekends are similar to those occurring on the weekdays. The following section will explore the patterns evident in the taxi travel data and discuss the results of several comparisons.

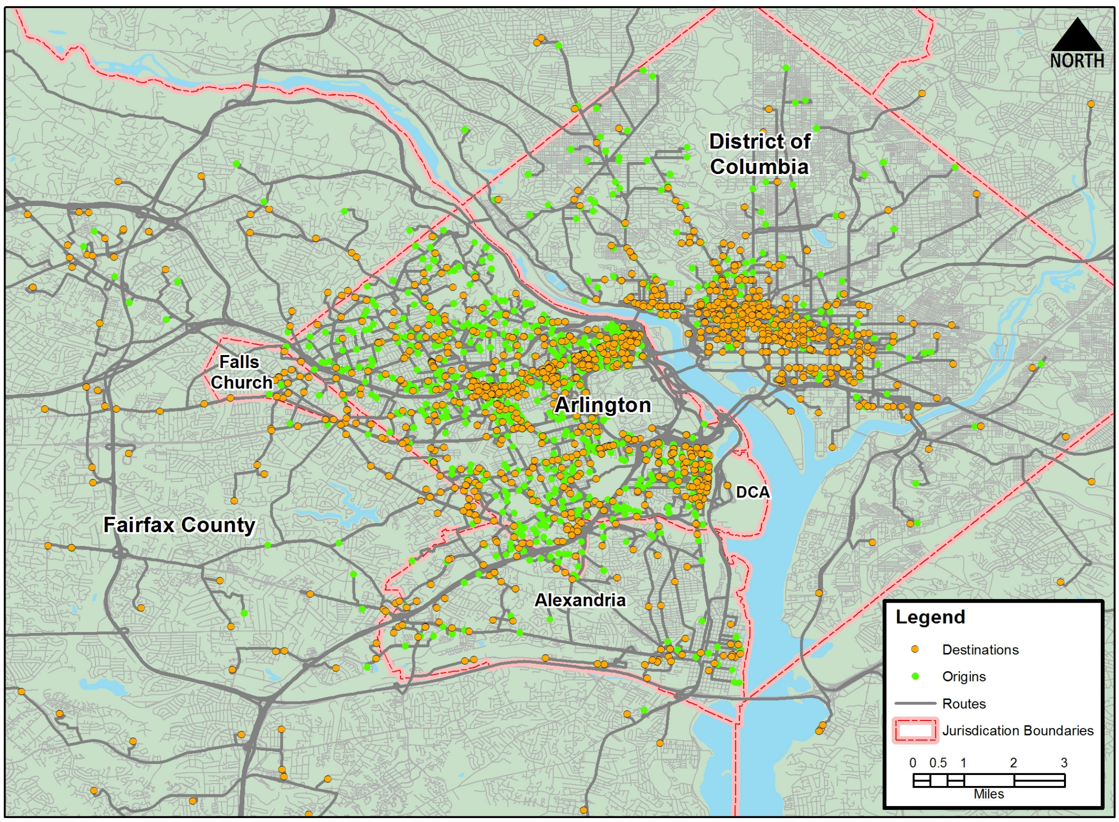


Figure 4 - Weekday Taxi Trip Routes

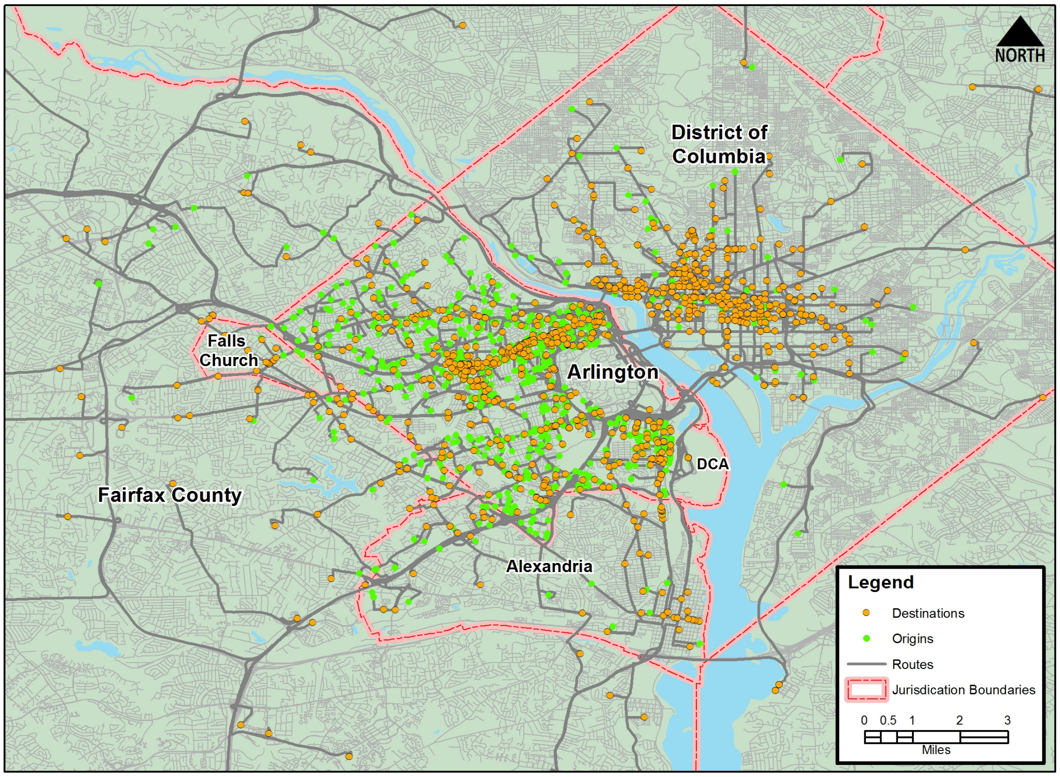


Figure 5 - Weekend Taxi Trip Routes

5.1. General Results

The results in Table 2 show that the typical taxi trip is short in distance and duration, less than $20 in cost, and usually contains only a single passenger. Table 2, summarizes the main descriptive characteristics of the taxi trips analyzed. A two-sample t-test was conducted to compare several of the statistics presented. A 99% certainty level was used for the comparisons and the t-test assumed differing variances. The average distance and fare were found to be statistically different for regular versus airport taxi travel. This supports the decision to analyze the two populations separately based on their trip purposes.

In addition to the difference between airport and regular taxi travel, the average occupancy was found to be different for regular weekend versus regular weekday taxi travel. The results in Table 2 suggest that the average occupancy on the weekend is higher than that of the weekday sampled. The reasons for this may be that there is a shift in trip purposes from the weekdays to the weekend. For example, during the week there may be more single passenger business-related taxi trips, while on the weekend trips are likely recreational and would be completed by multiple occupants, such as friends, couples, and families, for leisure or social activities.

The average trip distance for regular taxi travel was also found to be statistically different between weekday and weekend trips. However, the average distance for airport travel was found to remain consistent from the workweek to the weekend. Airport travel distance remains steady throughout the week, partly because the trips analyzed have consistent destinations. The consistent average distance for airport taxi trips also indicates that the pattern of origins is consistent. The difference in trip distance for regular taxi travel may be due a shift in destinations. For example, more residents may be taking taxis into the downtown DC area for recreational activities. This is supported by the results of the origin-destination tables presented in Table 4 and Table 5, which show that the percentage of trips into DC from Arlington increases from approximately 26% to 36% on the weekends.

Table 2 - General Characteristics of Taxi Travel

	Weekday		Weekend	
	Regular	**Airport**	**Regular**	**Airport**
Average Occupancy (passengers/trip)	1.31	1.29	1.57	1.33
Average Fare ($/trip)	14.71	21.97	13.49	19.70
Average Distance (miles/trip)	4.89	8.86	4.30	8.30
Number of Trips	1656	558	1285	226

5.1.1. Fare Composition

In addition to the parameters presented in Table 2, the relationship between distance and fare can be extremely useful to planners and taxi regulators. Figure 6 and Figure 7 depict the relationship between trip distance and fare for regular taxi travel over the two sample dates. The slope of the lines for weekend travel are greater than those for weekday travel, which suggests that the other components of fare, such as waiting time are more influential on the weekend than during the week. This could be due to the fact that a higher percentage of trips cross the heavily congested bridges between Arlington and DC on the weekend.

The different y-intercept values in Figure 6 and Figure 7 reflect the difference between single and double occupancy fares. This difference is $1.00 in reality, but the data show differences of approximately 60 cents and 50 cents for weekend and weekday travel respectively. All of the relationships between fare and distance follow a relatively well behaved linear model, which suggests that the role of delay in fare cost is not as significant as distance. This idea is supported by Figure 8, Figure 9, and Figure 11 in which there is not a strong linear relationship. The two clusters present in Figure 10 represent the target airports of DCA (Cluster 1) and IAD (Cluster 2).

These various relationships can aid in developing an idea of general mobility. For example, by examining the fare and distance relationship, the effect of congestion may be extracted. In addition, by investigating outlying clusters on the plot of fare and duration, planners may be able to identify problem spots where congestion and delay are prevalent and get a feeling for how the fare structure is behaving in pricing certain trips of interest.

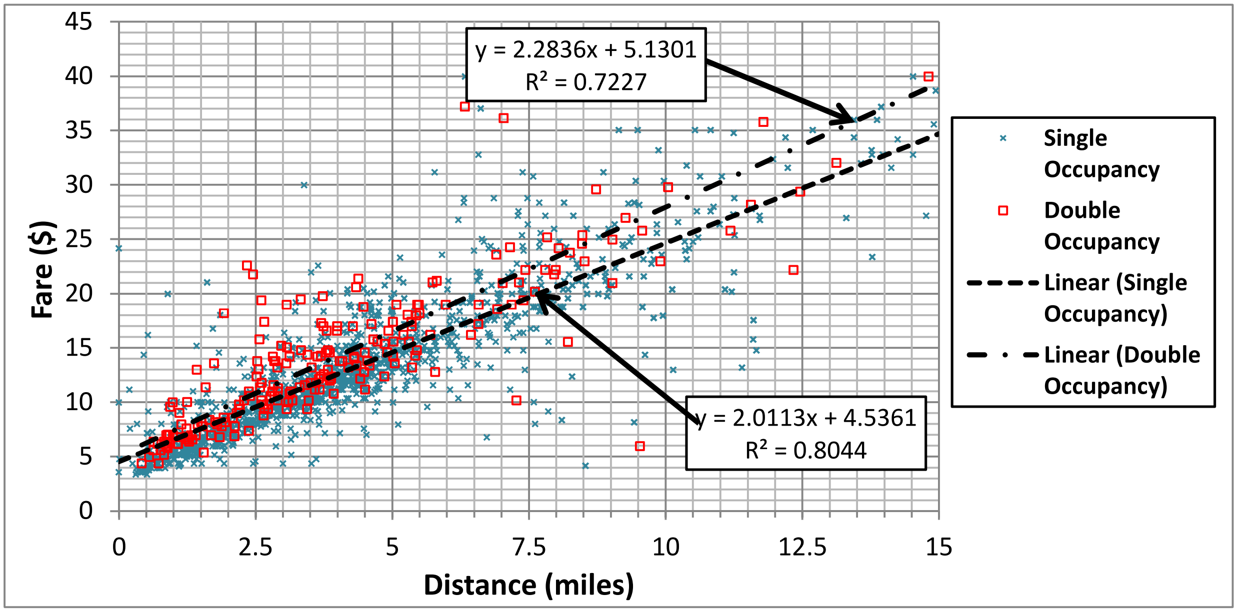


Figure 6 – Relationship of Trip Distance & Fare for Weekday Non-Airport Taxi Travel

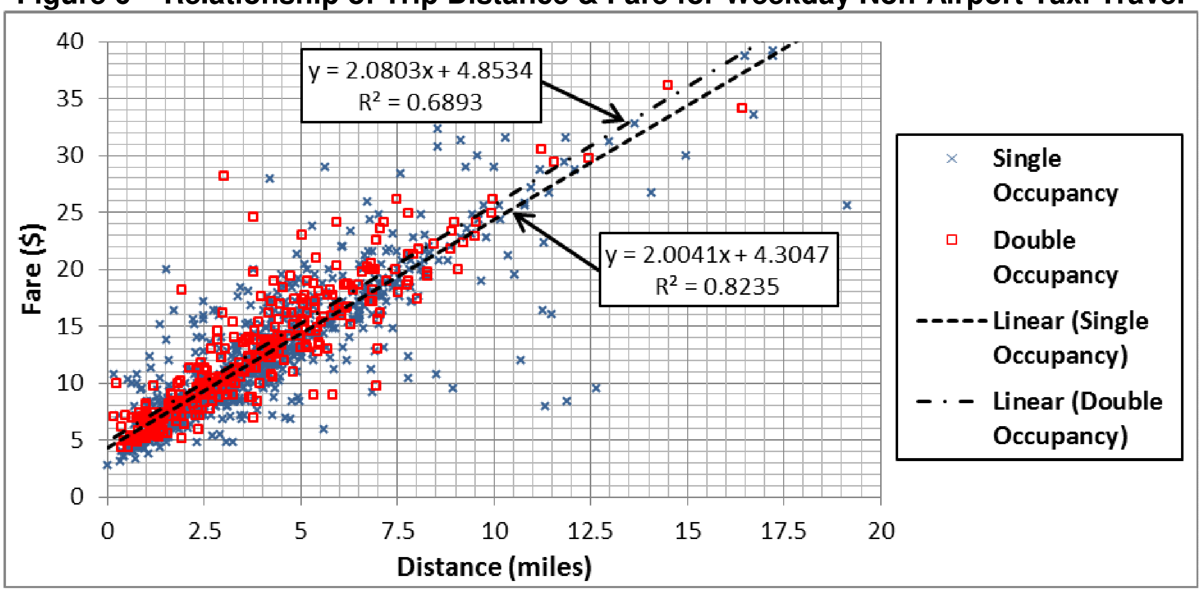


Figure 7 - Relationship of Trip Distance & Fare for Weekend Non-Airport Taxi Travel

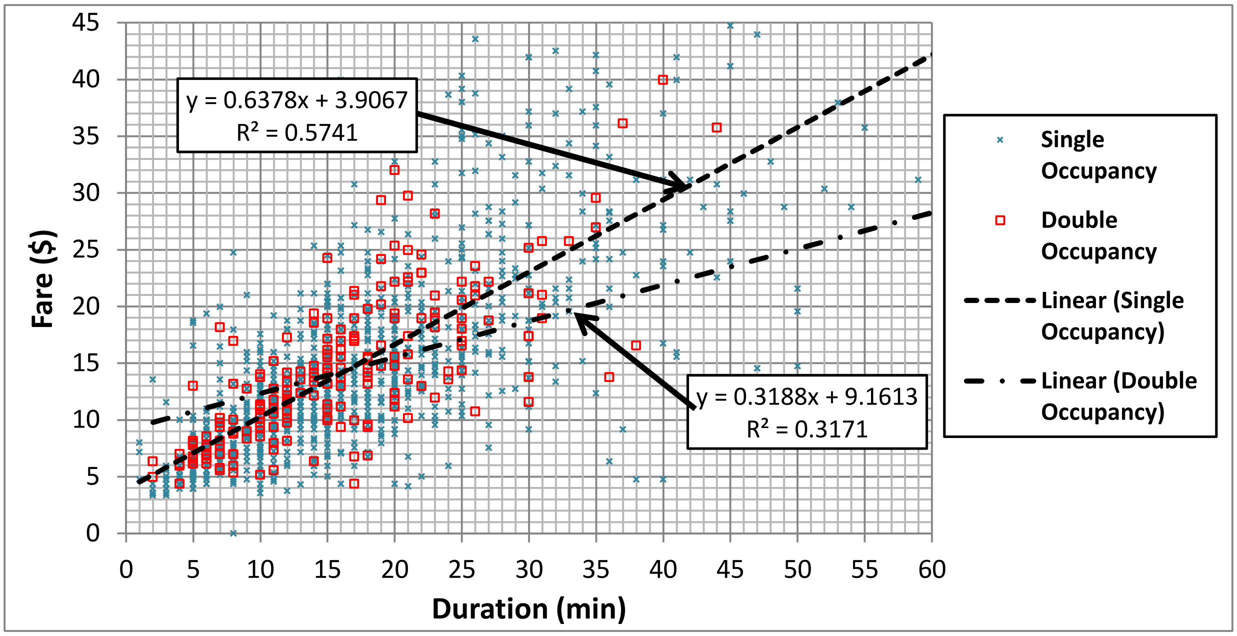


Figure 8 – Relationship of Duration and Fare for Weekday Non-Airport Taxi Travel

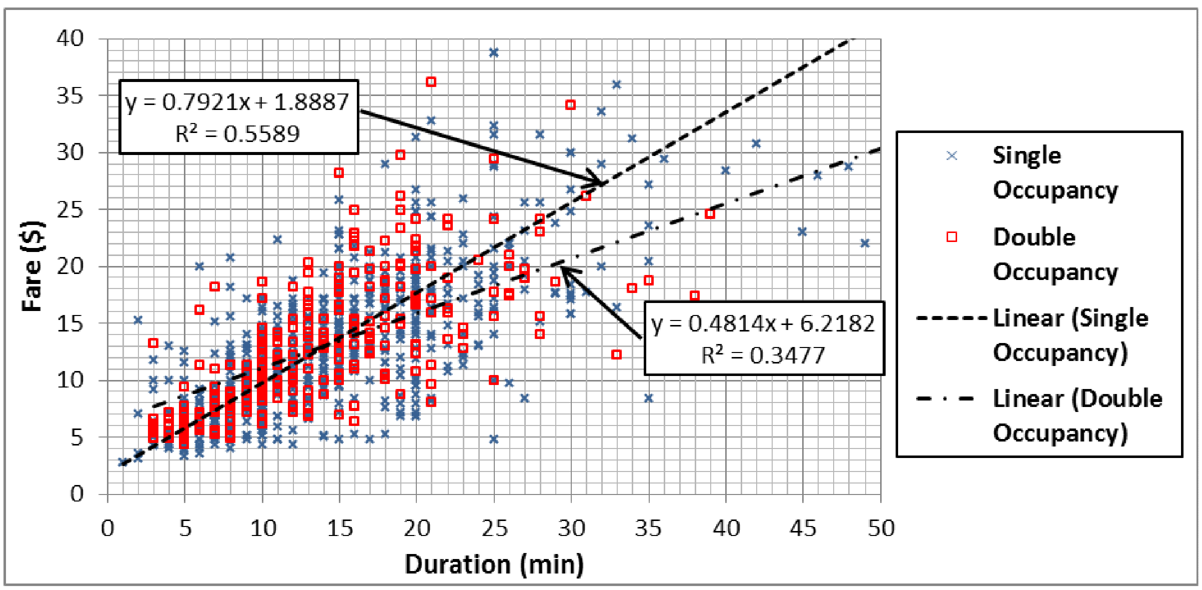


Figure 9 - Relationship of Duration and Fare for Weekend Non-Airport Taxi Travel

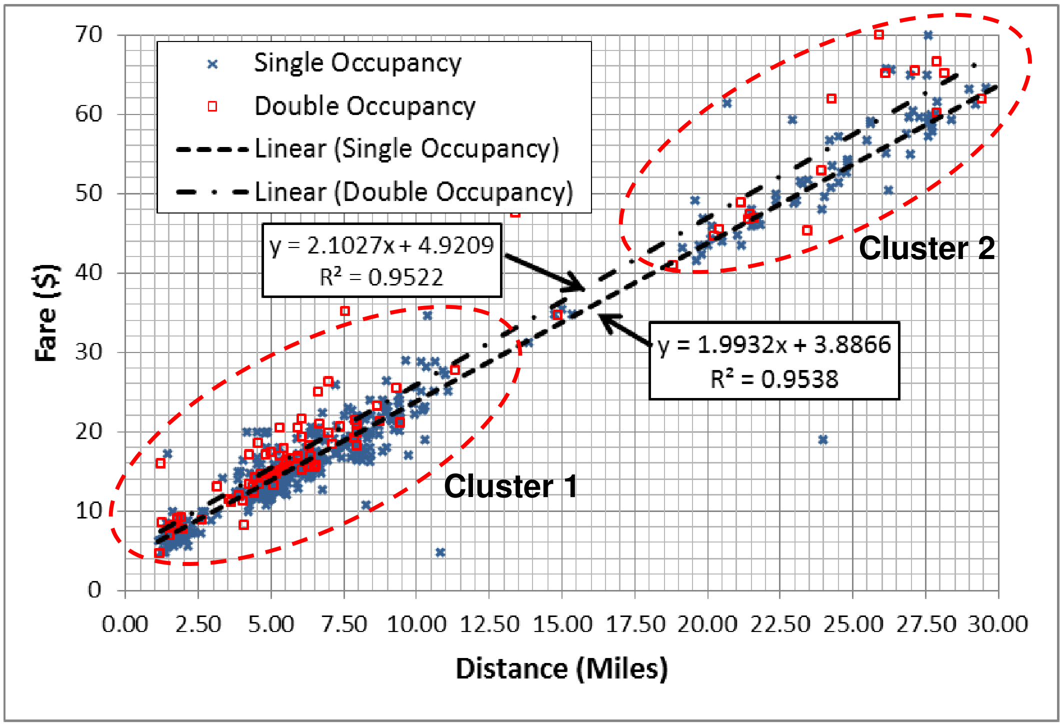


Figure 10 - Relationship of Trip Distance and Fare for Weekday Airport Taxi Travel

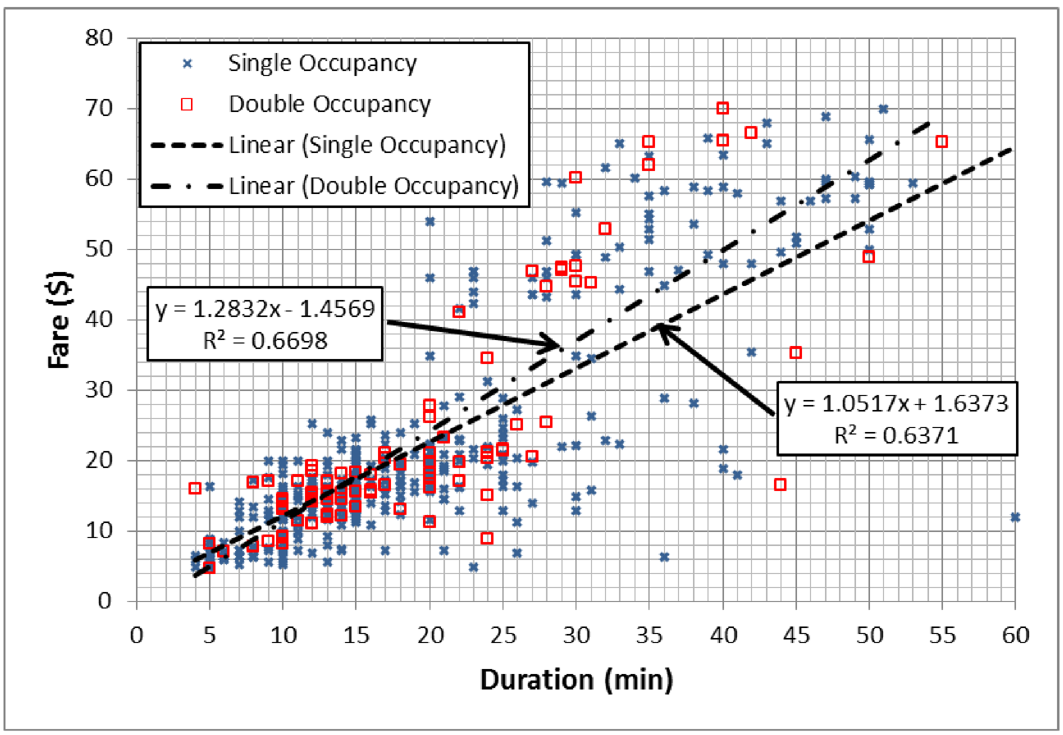


Figure 11 - Relationship of Duration and Fare for Weekday Airport Travel

5.1.2. Taxi Travel Speed

One of the fundamental performance measures in transit operations is speed. Taxi speed will vary greatly depending on the route taken, type of roads traveled, and degree of congestion. Still, having a general estimate of taxi travel speed can be a useful indicator of mode choice. Figure 12 and Figure 13 show plots of trip distance versus trip duration. From these plots it is clear that there is wide variation in the speed of a trip. The reason for this variability is that taxi trip duration may include waiting time; waiting time can include traffic delays or be at the request of the rider. However, the average speed seems to fall around 18 mph for both weekday and weekend travel. The two data samples were found to not have statistically differing means. This suggests that taxi speeds are relatively consistent between weekends and weekdays. It should also be noted that the trip durations are based on the manual records and are not as accurate or precise as electronic data. For example, a taxi driver may round up or down and only records to the nearest minute. This inaccuracy in time keeping may not be far from the users “perceived” travel time however. It is interesting to note that the average speed of Metrorail service was reported as 33 mph[21]. Generally travel by auto is quicker than by train. However, the effects of congestion in the Washington DC area are notorious and this could greatly influence the results.

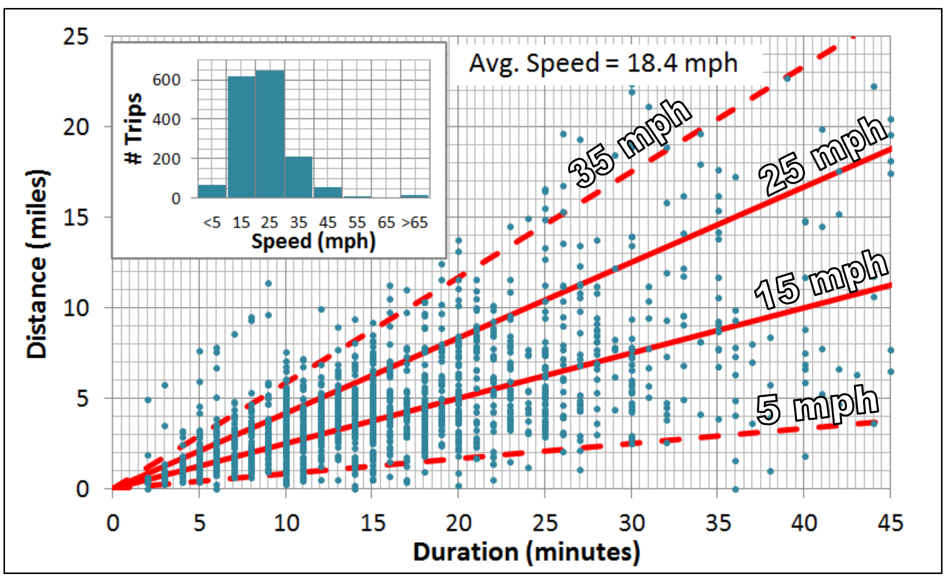


Figure 12 - Weekday Taxi Travel Speed

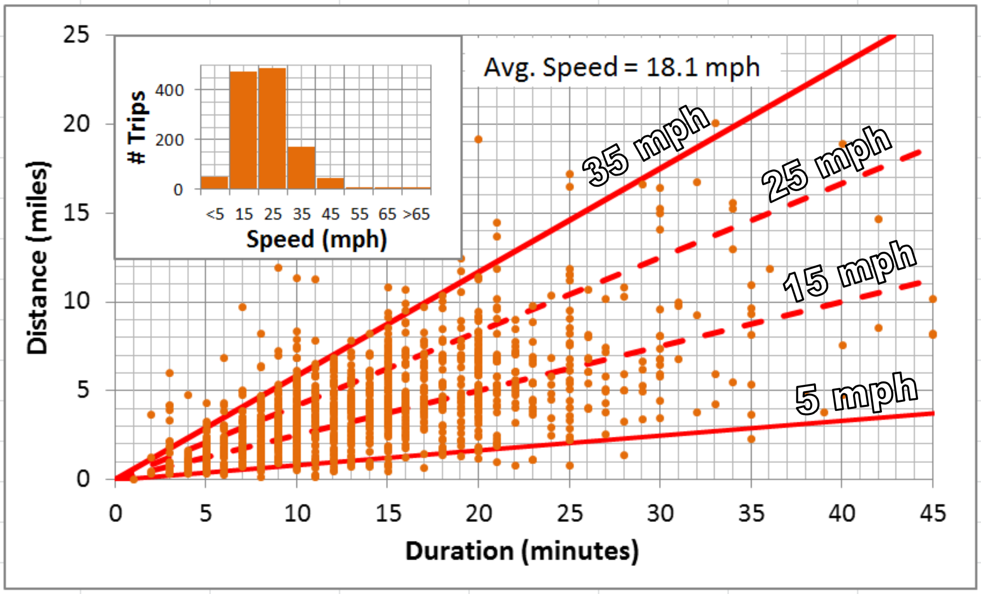


Figure 13 - Weekend Taxi Travel Speed

The comparisons between airport travel and non-airport travel and weekday and weekend travel presented above are repeated in parallel throughout the examination of various parameters of the taxi trip data. This section will progress through various taxi travel parameters following the comparison structure outlined above to examine the data in more detail.

5.1.3. Airport and Regular Taxi Travel Comparison

When discussing taxi travel, it is important to distinguish between trips to and from the airport and trips for all other purposes. The reason for this distinction is that airport-bound travelers use a different set of criteria to decide between mass transit and taxi. For example, when traveling to the airport users may consider factors, such as urgency, luggage, or unfamiliarity with the area. These factors may not weigh as heavily for trips with a different purpose, such as commuting to work, for example. In this thesis, the results for airport and non-airport taxi travel are examined separately.

Generally, airport travel comprised a significant amount of the total taxi trips provided. Airport trips made up 25% and 15% of the total sampled weekday and weekend trips respectively. This suggests that travel to the airport by taxi is more frequent on Wednesdays than on Saturdays. The increase in airport taxi trip frequency during the week is logical, since more business activities occur during the workweek. Table 3 shows that the number of flight departures was higher on the Wednesday sampled than on the Saturday sampled. In addition, the number of flight departures is higher on Sunday than on Saturday. Taxi travel to the airport most likely follows the same patterns of air travel, since taxis are a main mode of airport access.

Table 3 - Flight Departures for Dates of Interest at DCA (5 Largest Airlines)

Date	Airline					
	U.S. Airways	Delta	American Airlines	United Airlines	AirTran	SUM
SAT 4/24/2010	41	24	25	9	12	**111**
SUN 4/25/2010	59	29	30	12	11	**141**
WED 4/28/2010	68	32	30	16	11	**157**
TOTAL	**168**	**85**	**85**	**37**	**34**	**409**

SOURCE: Data from Bureau of Transportation Statistics, "Detailed Statistics: Departures" for DCA, http://www.bts.gov/xml/ontimesummarystatistics/src/dstat/OntimeSummaryDepaturesData.xml

5.1.4. Weekend and Weekday Taxi Travel Comparison

Travel during the work week is fundamentally different than travel on the weekends. Weekend travel does not include the many trips made to and from work. In addition, during the weekend, the daytime populations of the commercial areas are much lower. It is then perhaps expected that the number of recorded weekday taxi trips was higher than the number of weekend trips. The reasons for this may be twofold: first, the general taxi demand may decrease on the weekends because the total number of trips being undertaken is lower. Second, a portion of the late night taxi trips may not have been recorded simply because the drivers may be accepting a higher number of hailed trips and fail to record the details between trips. This is a source of possible systematic error in the data and will be discussed later in the thesis. Still, comparing the characteristics of taxi travel on the weekend against weekday travel can be helpful in examining the relationship to mass transit since the operations of transit also differ greatly from weekday to weekend.

5.2. Fare Distribution

Understanding the typical range of amounts that users are willing to spend on taxi travel is integral to evaluating their operation. Figure 14 and Figure 15 show the distribution of fares for weekend and weekday taxi travel. From these figures it is evident that the distributions of fares are skewed heavily towards the lower fares. The majority of trips are less than $20-even when traveling to DCA (IAD fares are upwards of $50). The following subsections will compare the distribution of trip fares for various categories of taxi travel.

5.2.1. Airport and Regular Taxi Travel Fare Comparison

The results show that airport trips have a higher average fare than trips for other purposes. This increase may be due to the fact that trips to IAD cost about $55, which is much higher than the typical fare for regular taxi trips. Even the shorter distance taxi trips to DCA incur an airport surcharge, which would increase the average fare. Airport travel may also include baggage handling fees or waiting fees that contribute to the higher average as well. Another feature to note is the relatively small percentage of trips to IAD when compared to the volume of travel to DCA. This trend is probably due to the competition from other services, such as Washington Flyer (exclusive provider of taxi service from IAD) or the Super Shuttle services. Overall, the distributions of fare support the evidence that airport taxi trips are usually more expensive than the trips provided for other purposes.

5.2.2. Weekend and Weekday Fare Comparison

The distributions of weekday and weekend travel seem to be almost identical, although the average fare is slightly higher on the weekdays. Even the airport distributions seem to follow similar distributions from weekend to weekday. This suggests that fare distribution is relatively consistent throughout the week.

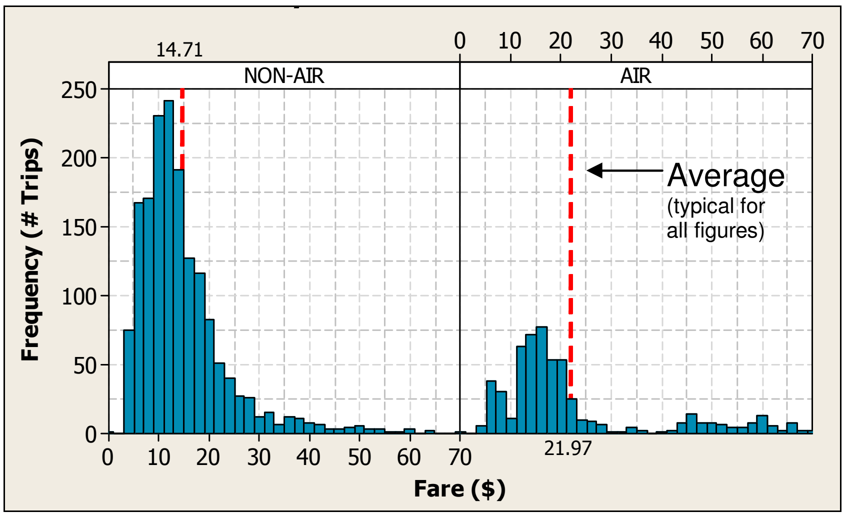


Figure 14 - Wednesday Taxi Travel Fare Distribution

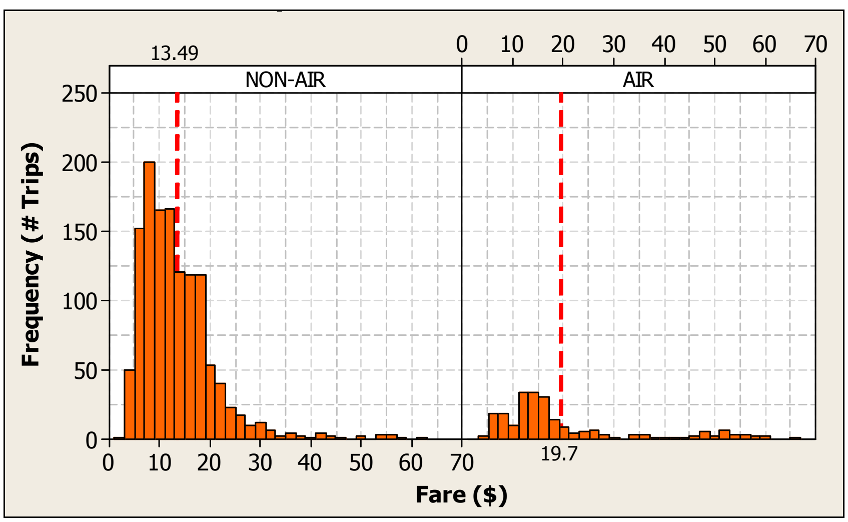


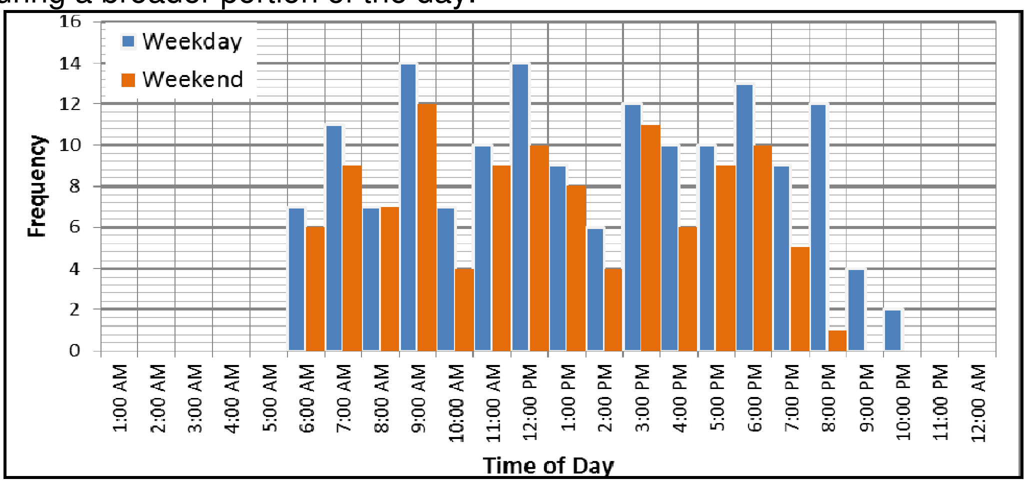
Figure 15 - Saturday Taxi Travel Fare Distribution

5.3. Time of Day Distribution

Taxis are often synonymous with late night atmosphere, but surprisingly, only a small amount of the total trips appear to occur during the late night hours. Figure 17 and Figure 18 show the distribution of trips across a 24-hour period for a Wednesday and Saturday respectively. The horizontal axes of the two figures are displayed in units of minutes. For ease of reference: 12:00 PM is represented by 720 minutes, 6:00 PM is represented by 1080 minutes and so on. The late-night peak is visible, but is dwarfed by the volume of trips occurring over the rest of the day and in particular, the morning hours. This may point to a major source of error in the manifest data if there were trips provided during these late night hours that were not recorded.

5.3.1. Airport and Regular Taxi Travel Time of Day Comparison

The airport trips display the dual peaking that would be expected to coincide with the morning and evening commuter flight frequency peaks. According to the data, there are fewer late night trips to the airports, which coincide with times when there are few or no departing flights. Since airport taxi travel is expected to follow flight departure frequencies, a list of the departure times for the flights at DCA on the sample dates of 4/24/2010 and 4/28/2010 were tabulated. Figure 16 shows the variation of the number of flight departures throughout the day for the five largest airlines serving the airport. This data follows closely with the frequency of airport taxi travel depicted in Figure 17 and Figure 18. The yellow arrows in Figure 17 highlight the dual peaking nature of the weekday airport travel. Regular taxi travel on the other hand, appears to show a more evenly distributed frequency throughout the day. In addition, regular taxi travel tends to occur during a broader portion of the day.



SOURCE: Data from Bureau of Transportation Statistics, "Detailed Statistics: Departures" for DCA, http://www.bts.gov/xml/ontimesummarystatistics/src/dstat/OntimeSummaryDepaturesData.xml

Figure 16 - Scheduled Flight Departures for Sample Dates (Largest 5 Airlines)

5.3.2. Weekend and Weekday Comparison

When compared, the weekend distribution shows less peaking and a more even distribution of travel throughout the 24-hour period. The lack of a significant peaking characteristic is due to the fact that there are no "rush hours" on the weekend. In addition, the late night peak is slightly more prominent on the weekend when compared to the weekday distribution. The late night peak is highlighted in Figure 18 by the yellow arrow. Both weekend and weekday airport taxi travel has consistent peaking characteristics.

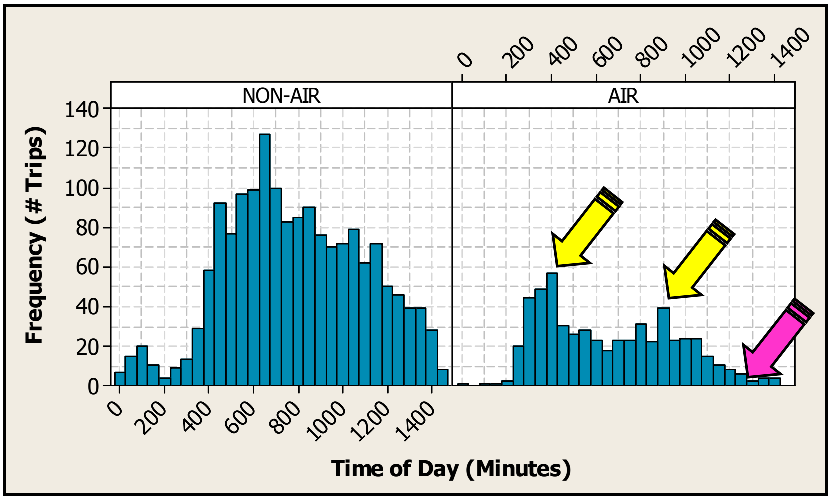


Figure 17 - Wednesday Taxi Travel Time of Day

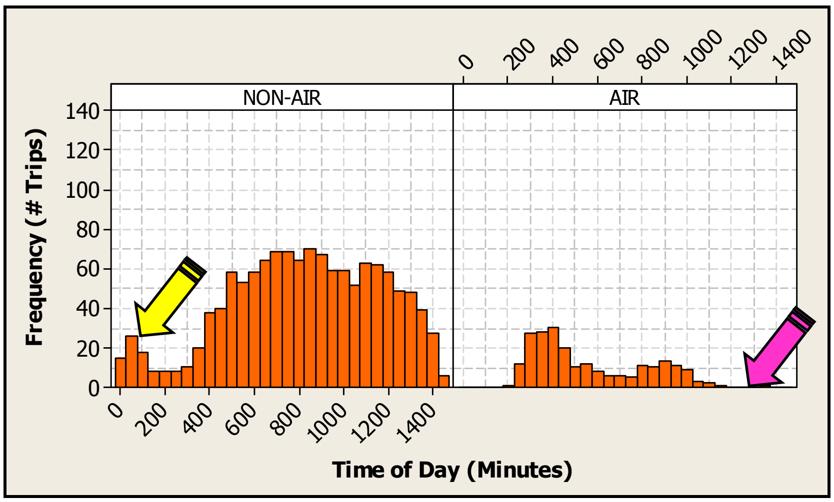


Figure 18 - Saturday Taxi Travel Time of Day

5.4. Trip Distance Distribution

Taxi fares are based at least partially on mileage and thus the distribution of the trip distances should follow that of the fares. Again it is important to note that the calculated distances are only estimations of the probable paths taken by the taxi drivers. In general, the distances seem to follow the same distribution as fares with most trips occurring over a distance of less than five miles. After five miles, the number of trips decreases significantly. This distribution follows the logic that many people simply use taxis for short trips and are more likely to choose a less costly mode for longer trips.

5.4.1. Airport and Regular Taxi Travel Time of Day Comparison

In general the airport trips follow the same distribution as the other trip purposes. However, there are several distinct characteristics present in the airport travel that are absent from the regular trips. First, there are two distinct peaks in the range of trips less than five miles. The first peak is likely the large number of trips from the nearby hotels in the Crystal City area to the airport. The second peak is likely the trips from the Rosslyn

–Ballston corridor. The gap between them is most likely caused by the location of Arlington Cemetery with respect to the airport. Arlington Cemetery is a region that generates little to no taxi travel to the airport, but separates the Rosslyn area from the airport. The gap is indicated by the yellow arrow. Finally, the slight grouping of trips in the longer distance range of more than 20 miles represent the trips to IAD, which is situated more than 20 miles from Arlington.

5.4.2. Weekend and Weekday Comparison

The weekend and weekday distribution of trip distance do exhibit small differences. First, there appears to be a shift towards the shorter trip distances on the weekend. Once of the reasons for this shift may be decreased mass transit operating frequencies. This possibility will be explored in more detail later in the thesis.

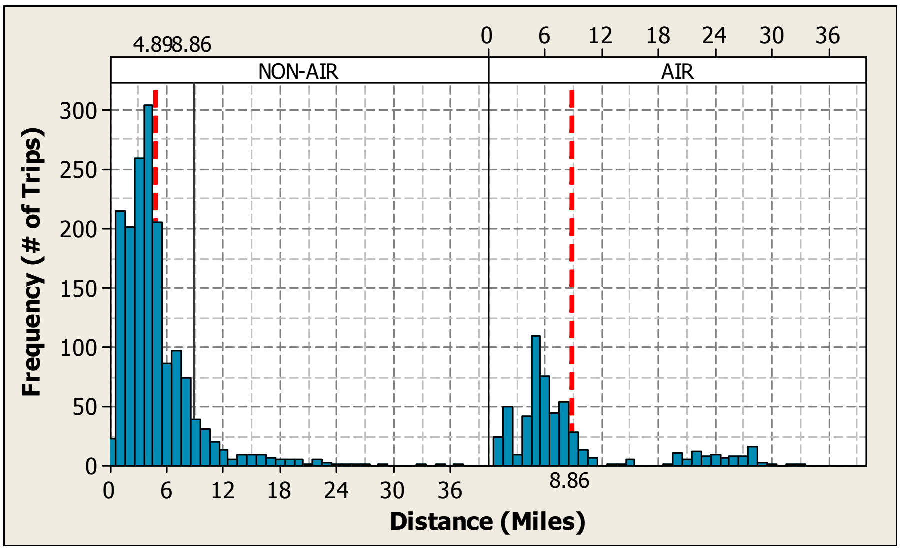


Figure 19 - Wednesday Taxi Trip Distance

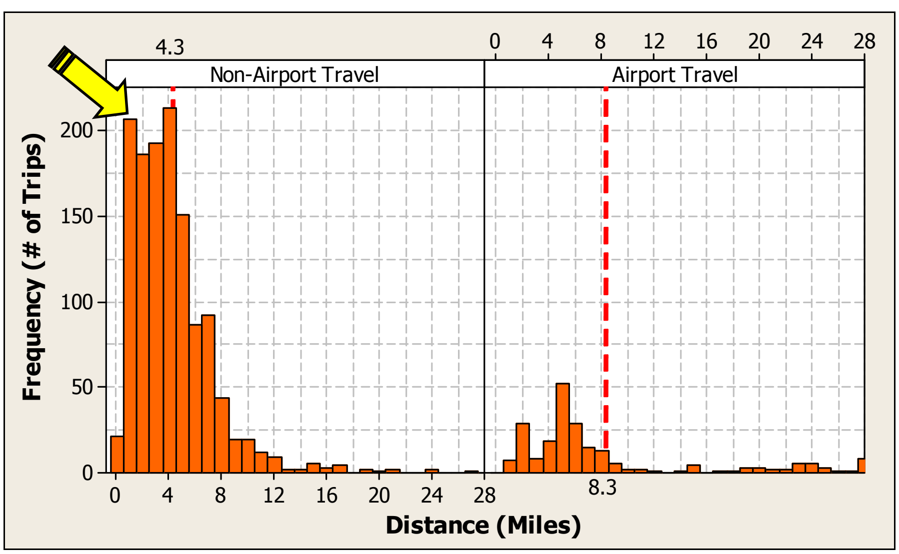


Figure 20 - Saturday Taxi Travel Trip Distance

5.5. Spatial Distributions

Spatially, the trips recorded by the manifests revealed many interesting patterns—some were expected and others were not. This section will present the spatial distribution of taxi travel in a series of maps depicting the geographic qualities of the various categories of taxi travel. To analyze the spatial patterns, the trips were separated into origins and destinations for weekday and weekend travel. In addition, the airport trip origins were analyzed. Finally, analysis zones were created to further analyze the travel patterns.

5.5.1. Developing and Analyzing Origin-Destination Tables

The OD analysis zones were developed by combining Census Tracts within Arlington with neighboring jurisdictional boundaries. Many of the Census Tracts within Arlington were combined for ease of analysis. Figure 21 shows the regional zones used for the OD tables while Figure 22 provides a view of the Arlington zones. Although these zones are perhaps over-simplified, the same procedure could be used with traffic analysis zones by planners. The zones were chosen in a way that captured the major Metrorail corridors within Arlington while not overcomplicating the results with a multitude of zones. The resulting OD tables are presented in the following section for reference.

Travel within Arlington accounted for 43% and 44% of the total weekend and weekday taxi travel. The OD tables presented in Table 4 and Table 5 show that travel to DC accounts for 26 and 36 percent of the total trips for weekday and weekend travel respectively.

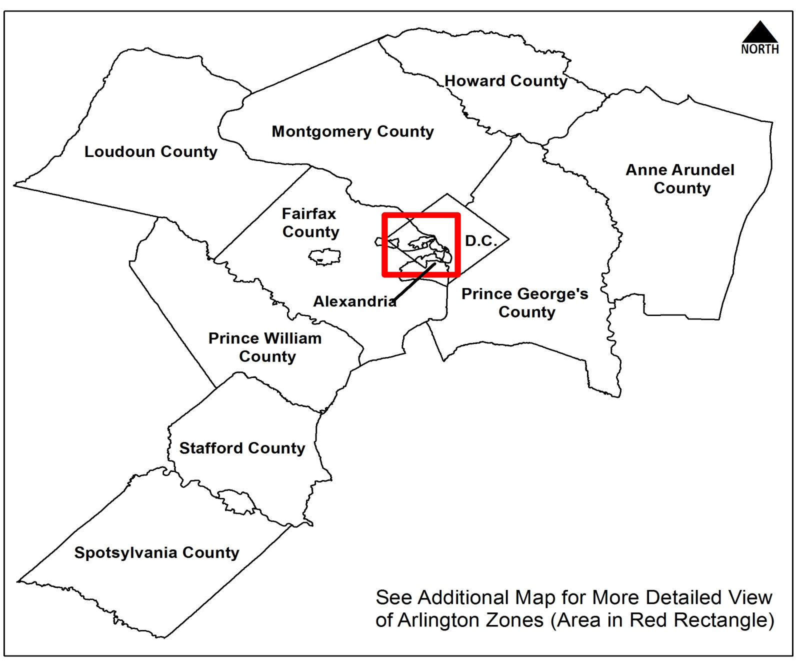


Figure 21 - Origin-Destination Zones (Regional View)

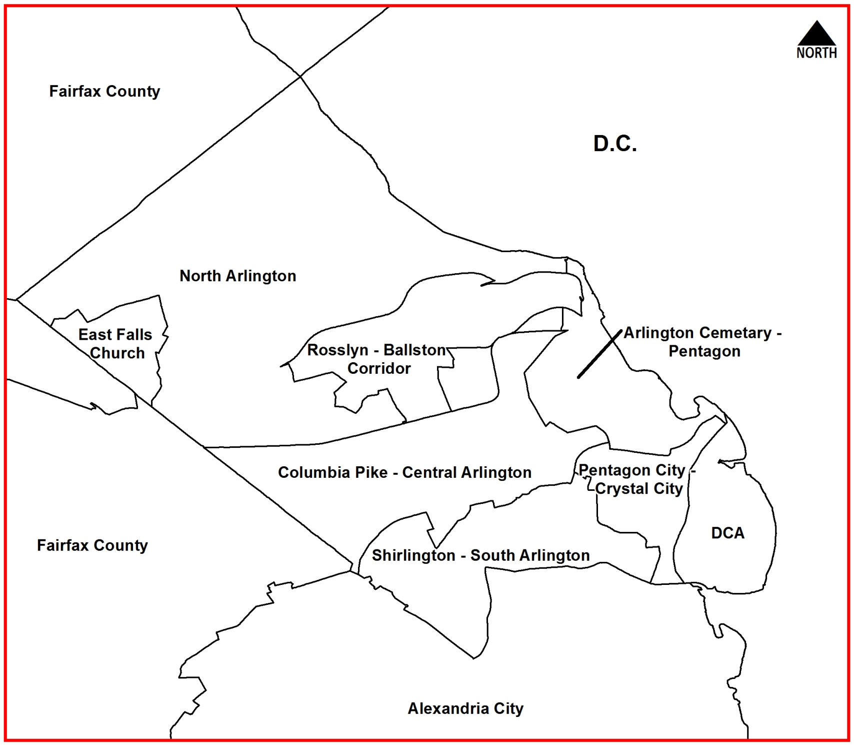


Figure 22 - Origin-Destination Zones (Arlington Area)

5.5.2. Metrorail Corridor Taxi Travel

The vast majority of the trips originated or terminated within the major Metrorail corridors. Approximately 49% of the weekday and 50% of the weekend taxi trips originated within either the Rosslyn-Ballston corridor or the Pentagon City and Crystal City Metrorail areas. Figure 23, Figure 24, Figure 25, Figure 26, and Figure 27 all show high concentrations of trips within the in the Metrorail corridors represented by larger circles. Arlington has long since adopted a strategy of “smart growth” in these areas, targeting high density development with a mixture of commercial and residential development. The dense land use along these corridors not only supplies a larger user population, but also encourages travel by modes other than cars. These factors create a larger rate of taxi travel in the Metrorail corridors. As mentioned previously, Crystal City contains a large number of hotels, which also explains the large number of taxi trips in the area.

5.5.3. Examination of Travel Patterns

Besides the high concentration of taxi trips in the Metrorail corridors, there are other interesting trends reflected in the data. Taxi use for transporting senior citizens and the disabled was discussed earlier; the results show that several trips originated and terminated at the Virginia Hospital Center (highlighted by the green arrow in Figure 23). Additionally, a number of trips terminated at Union Station, a major rail terminal in downtown Washington. Taxi travel to Union Station would indicate that the passenger is planning to take one of the regional rail services, such as the MARC, Virginia Rail Express (VRE) or Amtrak service, rather than Metrorail. In addition to these specific areas of interest, there is a general shift in the destinations that would be expected when considering weekday versus weekend travel. For example, the two areas indicated in Figure 27 are the Rosslyn area and the Pentagon. Both of these areas are major commuter destinations during the workweek, but on the weekend there is a significant decrease in taxi trips. Results such as this follow the intuitive reasoning for the flow of traffic and can be used to identify areas in need of improved access. For example, Union Station is directly accessible by Metrorail, but a high number of taxi trips might indicate that travel from Arlington to the station is cumbersome given the transit options. In reality, this inference may be true because traveling to Union Station requires a Metrorail rider from Arlington to transfer. The same line of thinking can be applied to the hospital location. The results show that taxi travel data can highlight patterns at both a macroscopic level and for specific trip attractors as well.

Table 4 - Weekday OD Table by Region of Interest

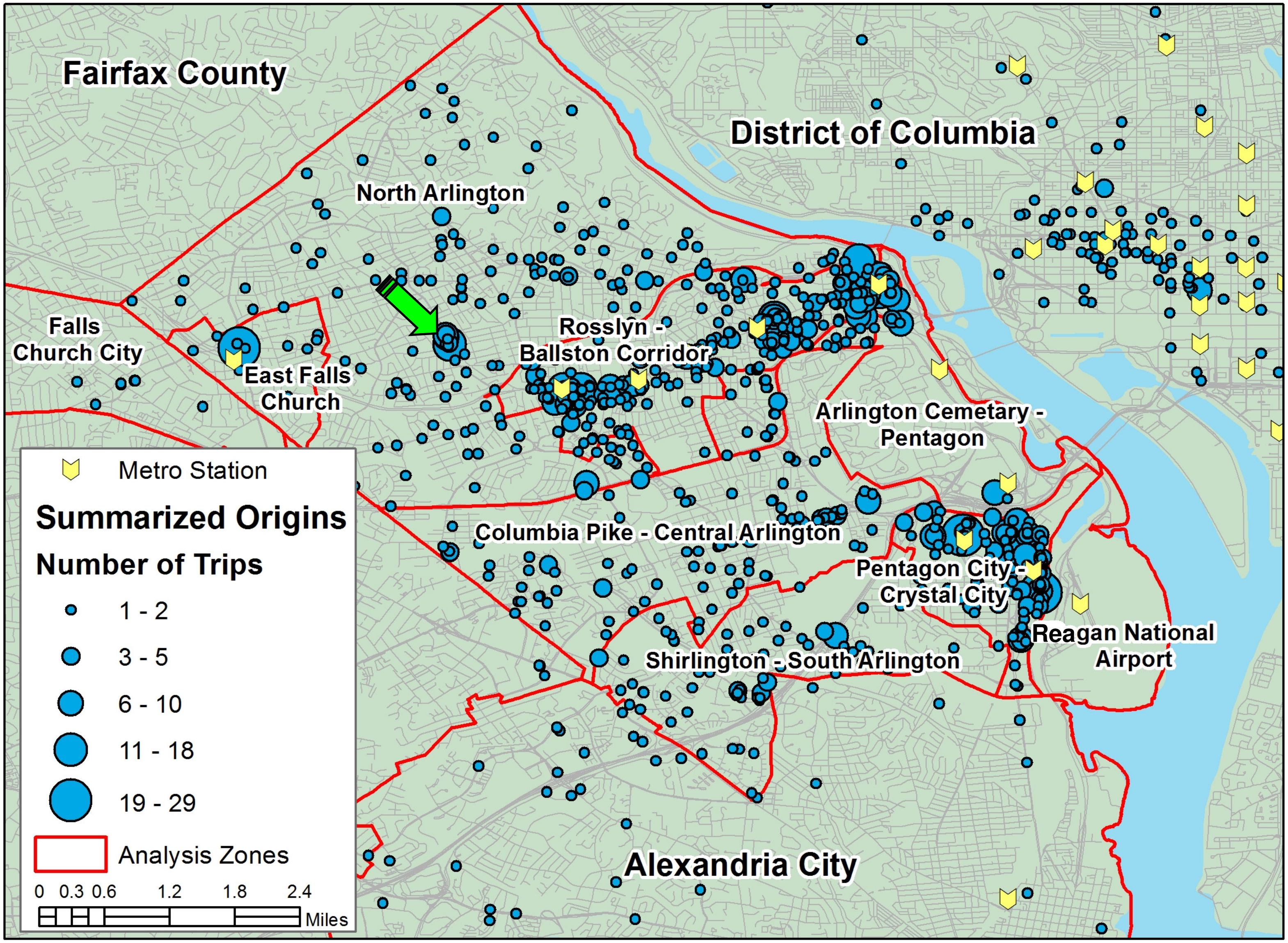
F\T	Alexandria city	Anne Arundel County	**Arlington Cemetery - Pentagon**	**Columbia Pike - Central Arlington**	**District of Columbia**	**East Falls Church**	Fairfax city	Fairfax County	Falls Church city	Fredericksburg city	Howard County	Loudoun County*	Montgomery County	**North Arlington**	**Pentagon City - Crystal City**	Prince George's County	Prince William County	**Reagan National Airport**	**Rosslyn - Ballston Corridor**	**Shirlington - South Arlington**	Spotsylvania County	Stafford County	**TOTAL**
Alexandria city	1			6	16			2				5		4	10	1		16	6	2			**69**
Anne Arundel County																							**0**
Arlington Cemetery - Pentagon	1			2	7			1							3			1	1				**16**
Columbia Pike – Central Arlington	11			16	44			13			1	2	1	17	13	1		23	30	8			**180**
District of Columbia	21		1	11	4	1		29	2			24		16	29	1	2	73	43	4		1	**262**
East Falls Church	1			2	4			13	11			2		3				5	3				**44**
Fairfax city																							**0**
Fairfax County	1			2	7	2		2				6		6	4			10	5	1			**46**
Falls Church city					1			1						3					1	1			**7**
Fredericksburg city																							**0**
Howard County																		1					**1**
Loudoun County																							**0**
Montgomery County				1											2			1	1				**5**
North Arlington	9			17	73	3	1	29	3	1		19	1	56	6			63	64	1			**346**
Pentagon City – Crystal City	15	1	4	20	163	1	1	15				11	4	9	37	6		72	20	6			**385**
Prince George's County																							**0**
Prince William County																							**0**
Reagan National Airport	2			1	2	1		2	1					6	5				8	2			**30**
Rosslyn – Ballston Corridor	11	1	4	26	249	1	1	28	3			22	5	55	30	8	1	147	107	8			**707**
Shirlington – South Arlington	9		1	7	32			5				1		3	9	1		24	14	10			**116**
Spotsylvania County																							**0**
Stafford County																							**0**
TOTAL	**82**	**2**	**10**	**111**	**602**	**9**	**3**	**140**	**20**	**1**	**1**	**92**	**11**	**178**	**148**	**18**	**3**	**436**	**303**	**43**	**0**	**1**	**2214**

*Trips to Loudoun County may include trips to IAD, which are permitted

Table 5 - Weekend OD Table by Region of Interest

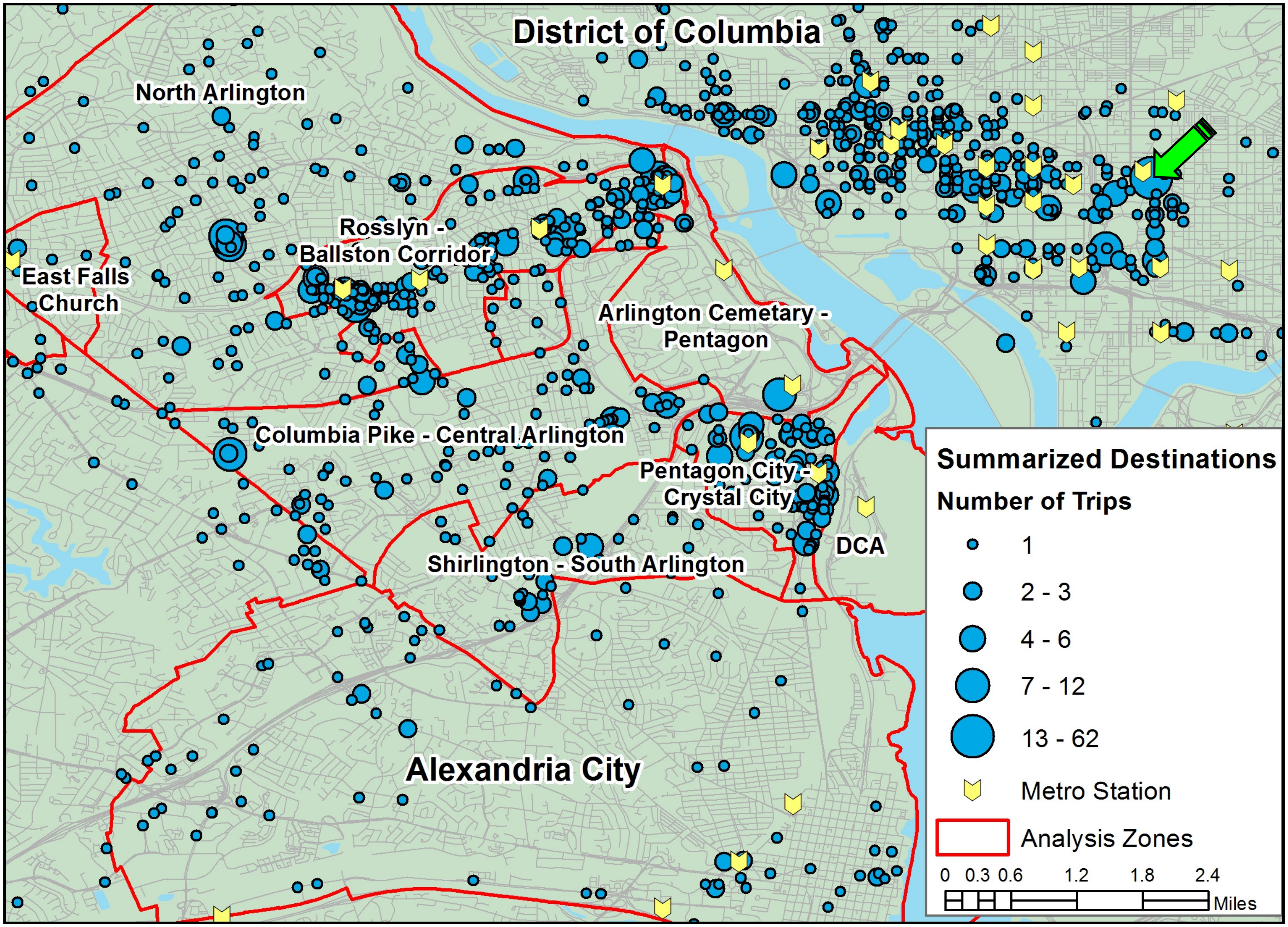
F\T	Alexandria city	Anne Arundel County	Arl. Cemetery - Pentagon	Columbia Pike - Central Arlington	District of Columbia	East Falls Church	Fairfax city	Fairfax County	Falls Church city	Fredericksburg city	Howard County	Loudoun County*	Montgomery County	North Arlington	Pentagon City - Crystal City	Prince George's County	Prince William County	Reagan National Airport	Rosslyn - Ballston Corridor	Shirlington - South Arlington	Spotsylvania County	Stafford County	TOTAL
Alexandria city	2			2	9							1		2	5			6	5	2			34
Anne Arundel County																							0
Arlington Cemetery - Pentagon					4									1	1			1	2	1			10
Columbia Pike - Central Arlington	2		1	12	36	1		11	2			3		14	8	1		16	29	7			143
District of Columbia	2			2	3	1		7	1			5		9	8		1	25	19	1	1		85
East Falls Church					6	2		4	4			2		1				1	1				21
Fairfax city																							0
Fairfax County				4	6	1		6				5		5				7	5				39
Falls Church city						1		1						2									4
Fredericksburg city																							0
Howard County																							0
Loudoun County																							0
Montgomery County																			1				1
North Arlington	10			7	120	4	1	11	2			7	1	26	5			22	79	6			301
Pentagon City - Crystal City	16			10	89			6	1			4		5	34	4		34	21	5			229
Prince George's County																							0
Prince William County																							0
Reagan National Airport	2				4			6	1				1						2				16
Rosslyn - Ballston Corridor	11	2		20	244	1	2	17	1			7		50	15	3	1	45	92	14			525
Shirlington - South Arlington	6			2	38			6				1		4	9			18	14	5			103
Spotsylvania County																							0
Stafford County																							0
TOTAL	51	2	1	59	559	11	3	75	12	0	0	35	2	119	85	8	2	175	270	41	1	0	1511

*Trips to Loudoun County may include trips to IAD, which are permitted



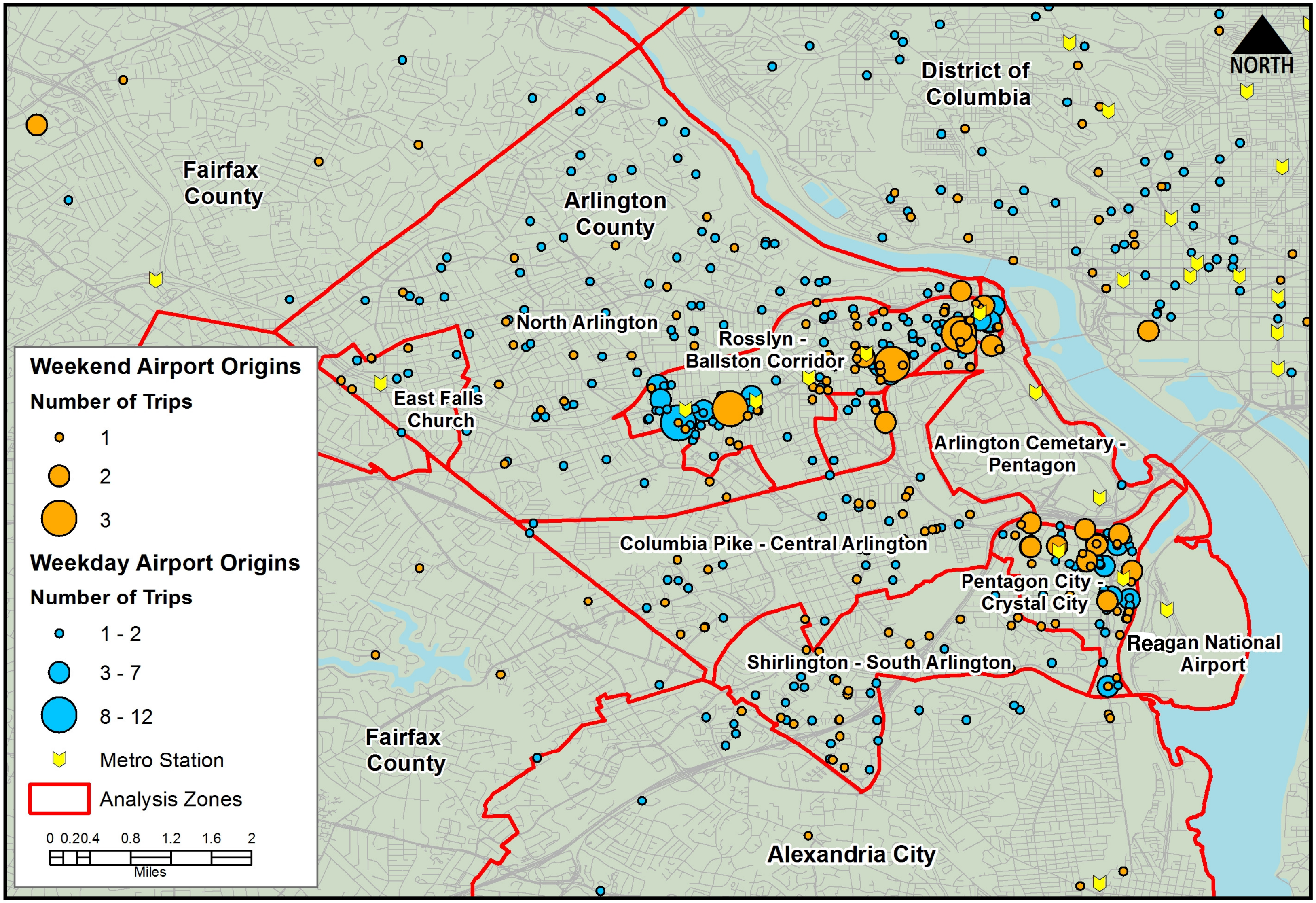
NOTE: The highest concentration of weekday origins occur in the areas identified as the Rosslyn-Ballston Corridor and Pengtagon City and Crystal City. The green arrow indicates the location of Virginia Hospital Center, the major health care center in the Arlington County.

Figure 23 - Spatial Distribution of Wednesday Non-Airport Taxi Travel Origins



NOTE: The highest concentration of weekday destinations occur in the areas identified as the Rosslyn-Ballston Corridor, Pengtagon City, Crystal City, and Northwest Washington, DC. There is a shift in spatial distribution across the Potomac in the destinations compared to the origins. The green arrow indicates the location of Union Station, a major rail terminal serviing Metrorail, VRE, Amtrak, and MARC rail services.

Figure 24 - Spatial Distribution of Wednesday Non-Airport Taxi Travel Destinations



NOTE: The highest concentration of weekday origins occur in the areas identified as the Rosslyn-Ballston Corridor and Pengtagon City and Crystal City. The yellow arrow indicates the location of Virginia Hospital Center, the major health care center in the Arlington County.

Figure 25 - Airport Origins (Wednesday and Saturday)

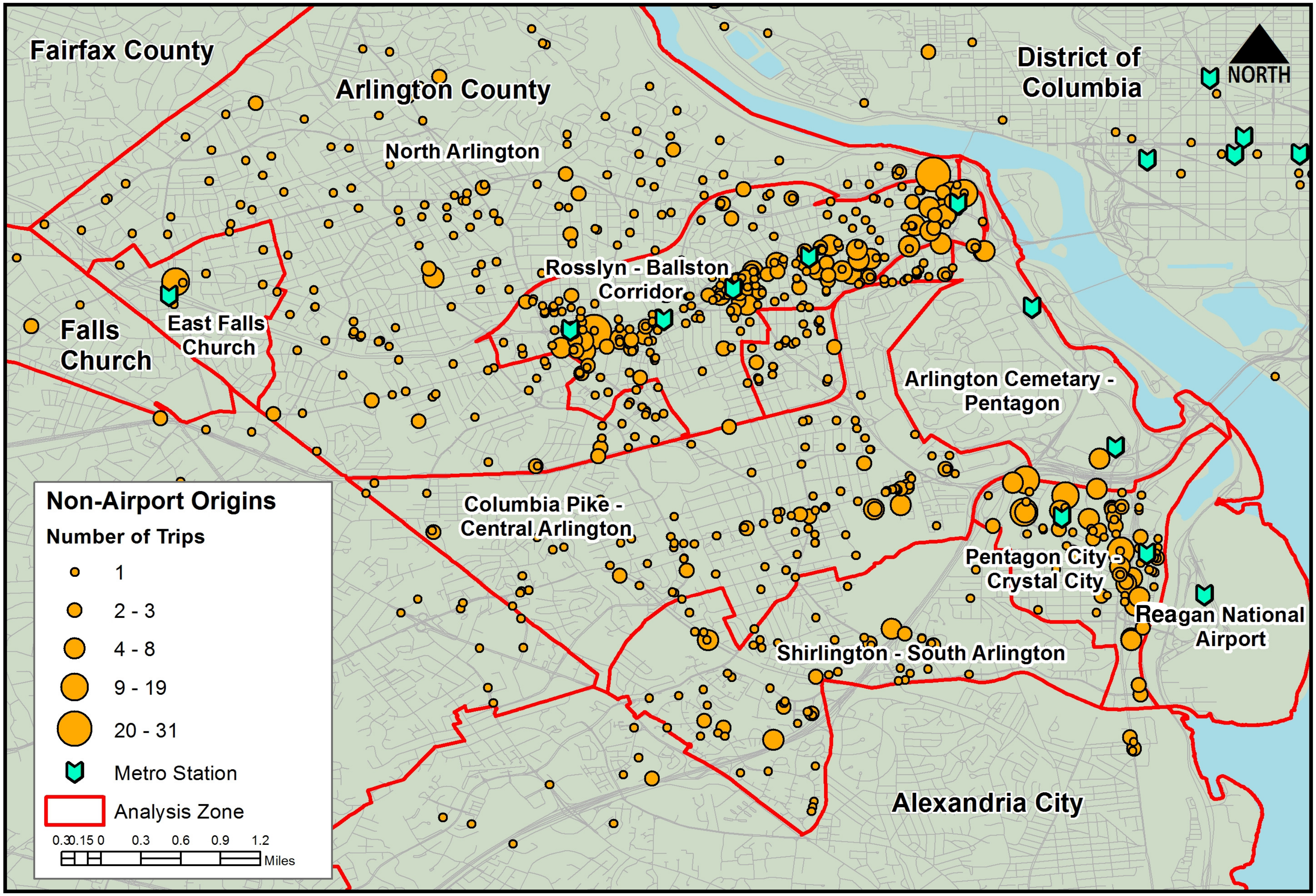
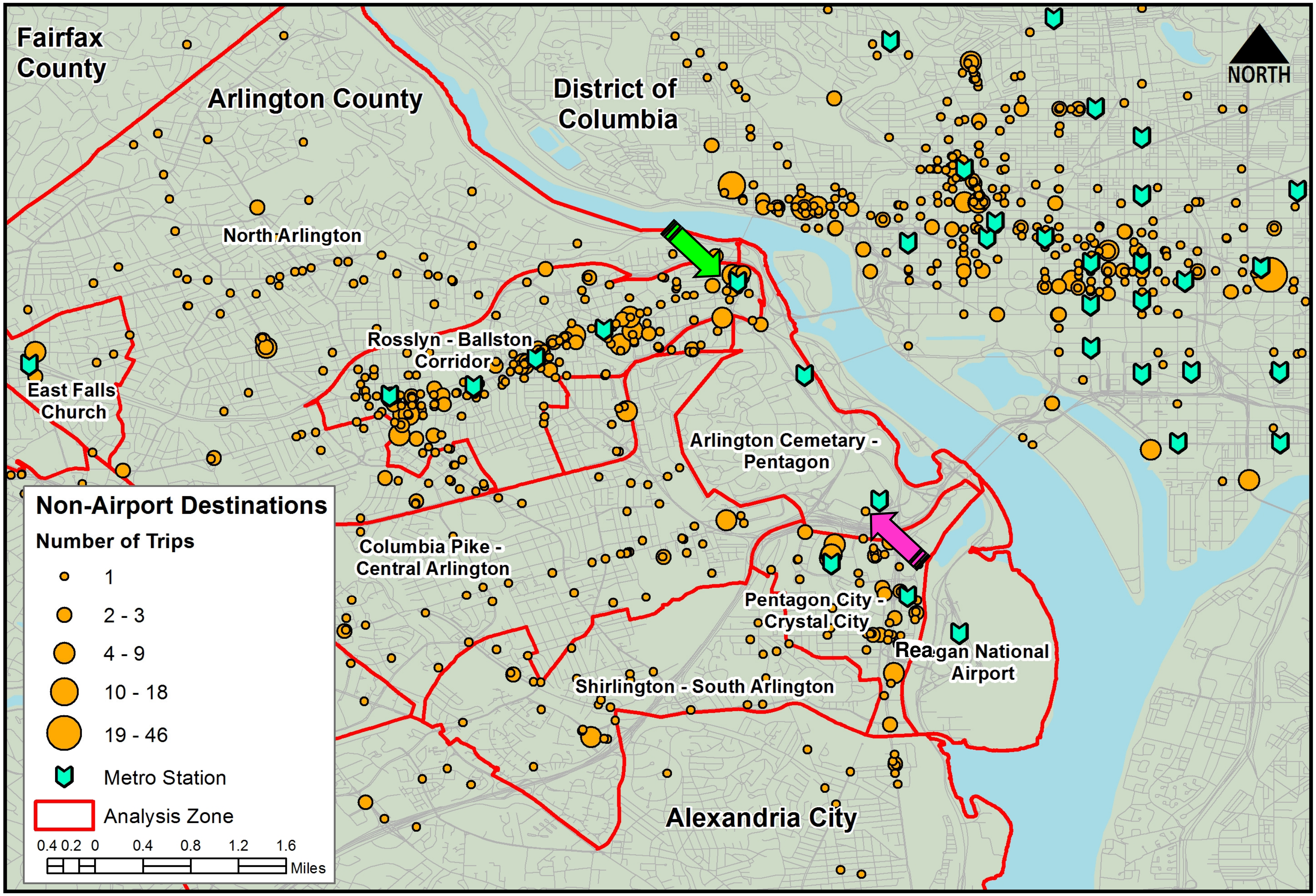


Figure 26 - Spatial Distribution of Saturday Non-Airport Taxi Travel Origins



NOTE: The weekend distribution follows the same general pattern as the weekday destination. There are much less frequent taxi trips terminating in the mainly commercial Rosslyn area (indicated by the green arrow) and at the Pentagon (indicated by the magenta arrow).

Figure 27 - Spatial Distribution of Saturday Non-Airport Destinations

5.6. Taxi Operations Efficiency

Many municipalities emphasize environmental impacts of transportation operations. In the past, effects such as fuel efficiency and air pollution may not have been as highly scrutinized as they are today. Today transportation facilities and operations are analyzed over an entire lifecycle that accounts for net energy consumption and pollution. Since taxi travel is an important part of public transportation, it is important to analyze their operation with the same attention to environmental impact as other public transportation options. In this spirit, the taxi manifests were examined to provide a rough estimate of the taxis' operating efficiency.

On a pure mileage basis, many factors come into play for taxicab operations. Unlike other forms of transportation like buses or rail, the vehicles can fall in and out of service at the discretion of the driver for the most part. The taxicab can then proceed to complete personal errands at the behest of the driver. In addition, unlike other forms of public transport, there is no guaranteed reciprocal demand. In other words, once a taxi makes one leg of a trip, there is generally not a predetermined user in the system that will occupy the cab for the "return trip". Instead, the taxi may search for fares or return to a stand. Because of these factors, there is often a large difference between paid and unpaid miles in taxi operations. To get a rough estimate of taxi efficiency, the total vehicle miles were compared to the total paid miles. Later in the thesis, fuel efficiency will be discussed for taxi travel operations.

5.6.1. Mileage Efficiency

For this research the mileage efficiency was defined as the ratio of paid miles to total miles. The results show that the average mileage efficiency for the taxis in this study was approximately 45%. Figure 29, shows the variation of the ratio of average paid miles to the average recorded miles throughout the week. From the data, it appears that the mileage efficiency is slightly higher during the workweek than on Fridays and Saturdays. This could indicate an increase in the number of hail trips or cruising on the weekend. In addition, the results show that the average total miles recorded on Friday are slightly higher than the rest of the week. This increase could be due to the fact that the Friday manifests may also include trips for Saturday if the drivers take the taxi home overnight. Figure 30 also shows the relationship of paid miles and unpaid miles to the total collected fare for each individual manifest. The tighter the cluster of green dots (unpaid miles) and the closer those dots appear to the brown dots (paid miles) the higher the efficiency. The relationship of fare and daily miles (both paid and unpaid) is presented for each day of the sample week. The paid miles follow a tighter linear trend while the total miles show more variation. From these plots, there appear to be more tightly clustered total miles from Monday through Thursday while the Friday, Saturday, and Sunday manifests show a greater spread. This trend could suggest that the taxi operations on the weekend are less efficient than during the week, but the effect of occupancy showed that the weekend travel is more efficient from a passenger movement standpoint.

An initial investigation shows that the taxi operations have higher mileage and lower efficiency on the weekends. However, the number of taxis operating also plays a significant role in these statistics. For example, the number of taxis sampled on the 23rd and 30th were 203 and 194 respectively whereas the number of taxis included in the weekday samples tended to be at least 30 taxis higher. The average daily trips provided also vary throughout the week. Figure 28 shows the variation in the average number of trips throughout the week; the results show that there is a higher number of trips provided on Friday and Saturday compared to the rest of the week. After considering these factors, the results still support the notion that weekend taxi travel is less efficient from a mileage standpoint than during the week. However, the next section will examine the impact of considering passenger occupancy on efficiency.

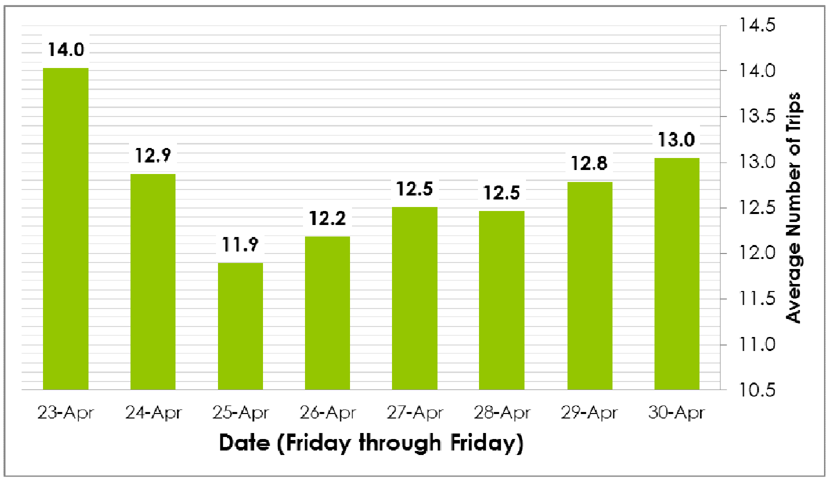


Figure 28 - Average Number of Recorded Trips

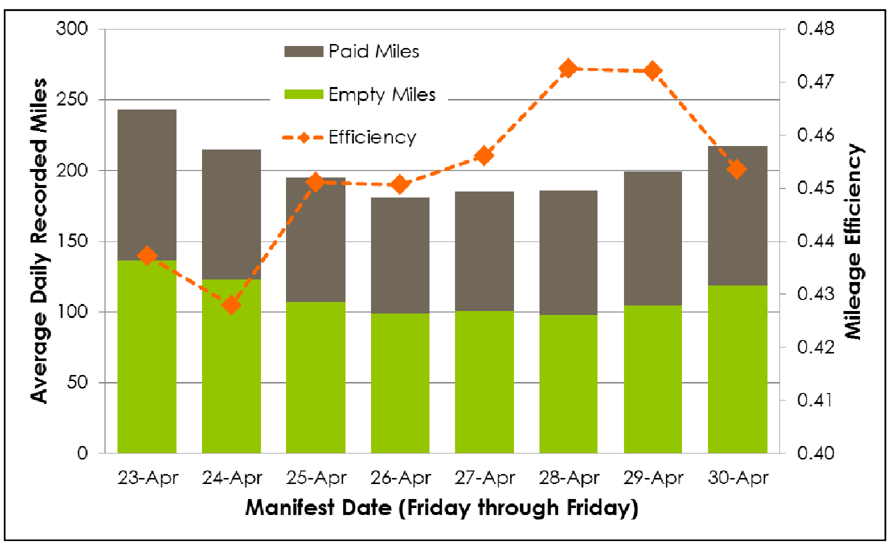


Figure 29 - Arlington County Taxicab Mileage Efficiency

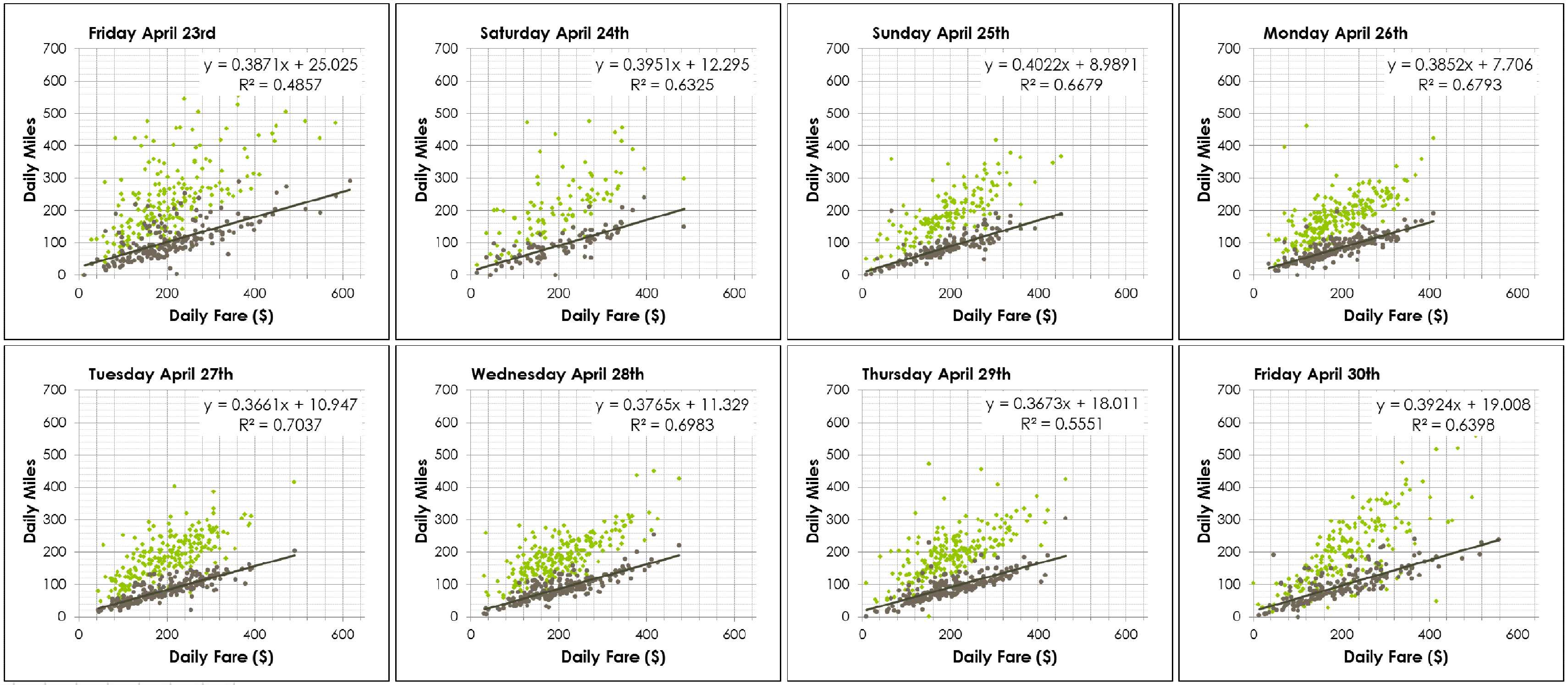


Figure 30 - Comparison of Daily Paid and Unpaid Miles to Fare

5.6.2. Vehicle Utilization

The results of considering occupancy in efficiency show that weekend travel may in fact be more efficient than weekday travel. The average passenger-mile efficiency is around 20% for the taxi manifests sampled. This means that the vehicle is only occupied for 1 out of every 5 miles. The significance of this number in comparison with other transit modes is discussed in Chapter 5 of this paper.

To determine how many passenger-miles were provided for each day of the week, an average occupancy was assumed. The average occupancy was generated based on the two detailed sample days. For the calculation of the vehicle utilization efficiency, Friday was considered a weekend day since it was considered to share many of the characteristics of Saturday travel. When compared to the results of vehicular mileage efficiency, these results show that weekend rather than weekday taxi travel is more efficient; this result is due to the higher number of multi-passenger trips on the weekend. In other words, although the number of cabs operating is less, the average number of trips and occupancy is higher, and the total passenger miles are more.

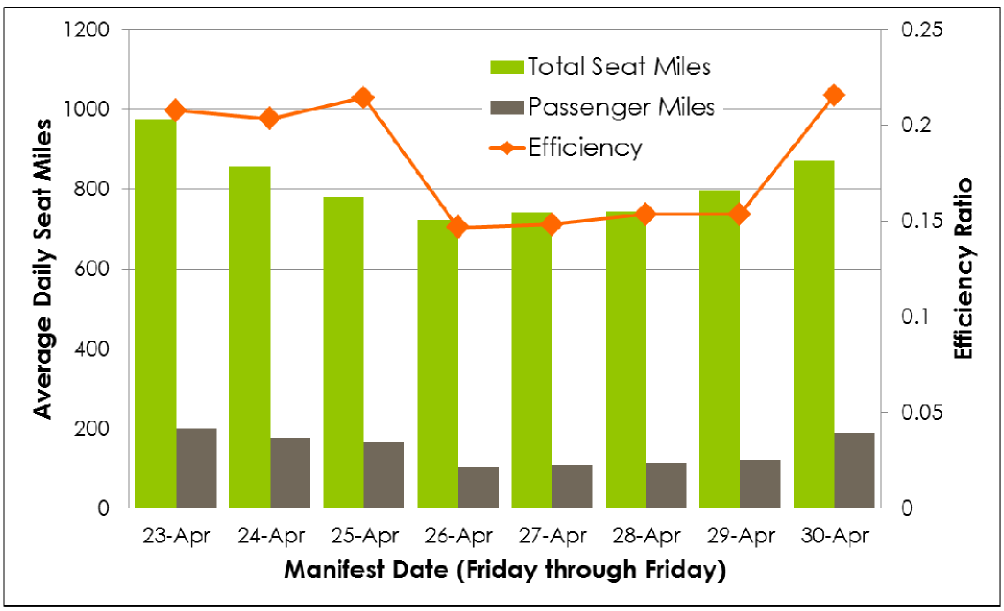


Figure 31 - Passenger Mile Efficiency

5.7. Summary of Taxi Travel Characteristics

The exploration of the taxi travel characteristics have resulted in a variety of useful results. An investigation of the basic parameters showed variations between airport taxi travel and regular taxi travel. In addition, weekday and weekend taxi travel were found to be different. The various results for the operational parameters are summarized below:

- weekday taxi travel has higher volume than weekend taxi travel
- weekend taxi trip occupancy is higher than on a weekday
- weekend passenger movement may be more efficient than on a weekday

- average taxi travel speed is about 18 mph
- weekend taxi trip fare and distance are higher than on a weekday

In addition to these parameters, the taxi travel patterns were examined from a geographic standpoint as well. The important results from the analysis were:

- a higher percentage of trips occur from Arlington to DC on the weekend rather than on a weekday
- taxi travel is intensified in the areas surrounding the Metrorail stations

These results may seem limited to a specific geographic context, but the ability to use the data to analyze taxi operations is the greater opportunity presented. These characteristics can allow for a better understanding of where people need taxis and how the taxis operate. The next section of the paper will attempt to use the taxi data to relate taxis to mass transit.

6. Relating Taxi Travel to Transit

The relationship between mass transit services and taxi travel are explained in detail in the following sections. Distances to the nearest transit facilities were computed for each taxi trip origin and destination. In addition to geographic data, the time of taxi travel is also revisited with respect to operating schedules of the local transit modes. Finally, transit efficiency is briefly compared to the sampled taxi population.

6.1. Proximity of Taxi Trips to Mass Transit Facilities

A fundamental disadvantage of mass transit is also the key advantage of taxi travel; mass transit use depends on access, taxi use does not. The taxi will come to the user while the user must travel to transit. Therefore, one of the main factors considered in deciding between taxi and mass transit use will be the difficulty of accessing transit facilities. The "distance to transit" was calculated as the amount that a bicycle or pedestrian would have to travel to access the transit facilities. The average distance to various transit facilities are summarized in Table 6. These averages were calculated only for distances less than 3 miles, as this was considered the cut-off value for access. In reality, the maximum distance that pedestrians might travel would be much less than 3 miles, but this value was chosen to account for possible bicycle access. Table 7 summarizes the percentage of taxi trip nodes that were found to be "inaccessible" by each transit type. The following subsections will explore the results and relate them to the three transit modes evaluated.

Table 6 - Average Distance to Nearest Transit Facility (Miles)

Transit Types	Weekday			Weekend		
	Regular		Airport*	Regular		Airport*
	Origins	Destinations	Origins	Origins	Destinations	Origins
WMATA Bus Stop	0.11	0.12	0.17	0.12	0.09	0.17
ART Bus Stop	0.41	0.82	0.62	0.32	0.91	0.65
Metrorail Station	0.66	0.66	0.65	0.75	0.59	0.79

*Distance from Destinations to transit omitted for Airport Travel because of consistent destinations

Table 7 - Percentage of Trips >= 3 Miles Away from the Nearest Transit Facility

Transit Types	Weekday			Weekend		
	Regular		Airport*	Regular		Airport*
	Origins	Destinations	Origins	Origins	Destinations	Origins
WMATA Bus Stop	0.12%	0.79%	0.54%	0.16%	0.62%	0.44%
ART Bus Stop	6.60%	27.91%	13.08%	3.58%	22.72%	9.73%
Metrorail Station	5.75%	8.41%	7.35%	4.82%	6.07%	7.08%

*Distance from Destinations to transit omitted for Airport Travel because of consistent destinations

6.1.1. Metrorail and Taxi Trips

Based on the results presented, Metrorail seems to be the most consistent form of transit for completing the trips taken by taxi. The average distance from the taxi trip origins and destinations to Metrorail stops was less than ¾ of a mile for both weekend and weekday and airport and non-airport travel. Unlike ART and WMATA, if both the origin and destination are in proximity of a Metrorail station, the maximum number of transfers that a rider will have to make is one. The results show that the Metrorail stations could offer a viable alternative option to taxi travel. However, the effect of service frequency and time of day should also be examined.

The results show that the many of the trips are located relatively nearby existing Metrorail stations. Intuitively, one would expect the rate of taxi travel to increase farther from the Metrorail stations, but instead the results show that the vast majority of taxi travel occurs in close proximity to the stops. This result is most likely a function of the land use and population density surrounding the metro stations.

The weekday and weekend sample days show almost identical distributions. The weekend trips seem skewed towards the lower distances than the weekday trips, which suggests that there are other factors at play, most noteably the operating frequency of Metrorail on the weekends. Another explanation might be that tourism increases on the weekend and these tourists may be unfamiliar of uncomfortable with transit options, such as the Metrorail system. The annotated arrows in Figure 32 and Figure 33 highlight the marked increase in the frequency of trips originating close to the Metrorail stations. Overall, the proximity of the trip destinations to metro seemed to be distributed in a similar manner for both weekend and weekday travel.

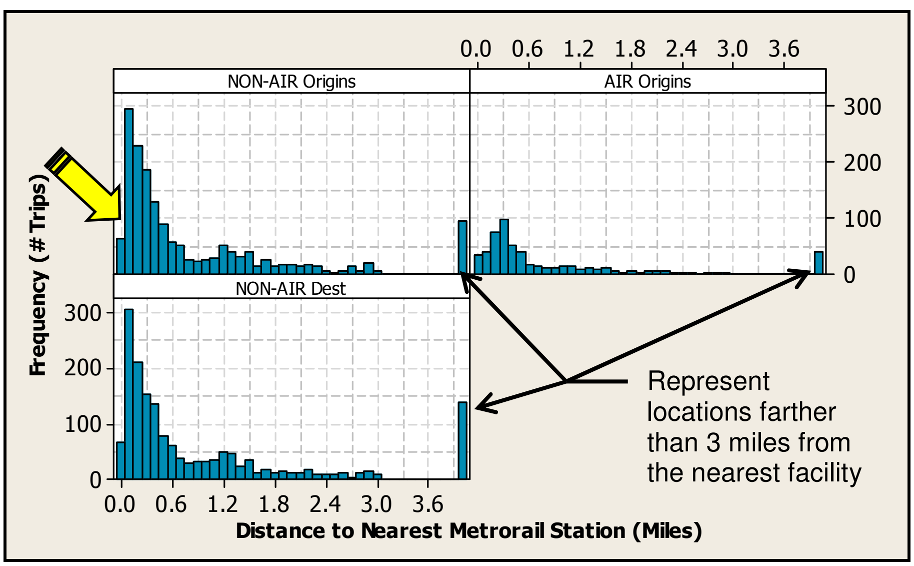


Figure 32 - Proximity of Wednesday Taxi Trips to Metrorail Stations

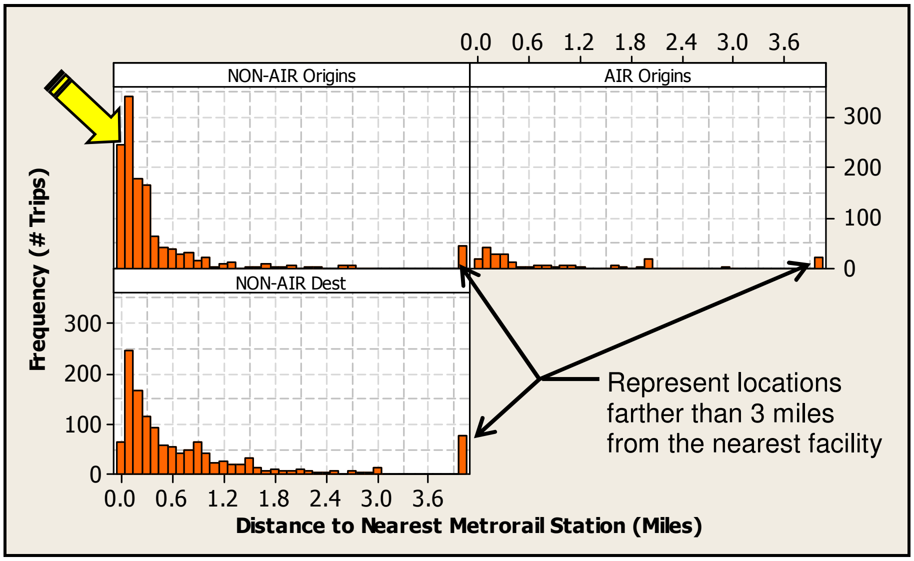


Figure 33 - Proximity of Saturday Taxi Trips to Metrorail Stations

6.1.2. Arlington Regional Transit (ART) and Taxi Trips

Given the collector and circulatory function of the ART bus service, it follows that they are generally the farthest facilities from taxi trip nodes. Among the three transit modes evaluated, the highest percentages of taxi trip destinations were not accessible from ART bus stops. On the other hand, only about 7% of trip origins were not within three miles of an ART stop, and the average distance from a taxi origin to the nearest ART stop was less than a half mile. This suggests that the ART bus service provides enough coverage to collect the majority of taxi trip origins and funnel the user into other modes of transit. However, this also means that ART use often would require a transfer to another transit mode, thus making mass transit less appealing in comparison to taxi.

The distance from taxi trips to the nearest ART stops are distributed in a similar manner to the WMATA bus stops. However, a much higher percentage of destinations were inaccessible by ART (28%) compared to just 1% by WMATA bus. This large number of inaccessible destinations is highlighted in Figure 34 by the yellow arrow. However, ART bus service is generally meant to funnel passengers into the other transit systems. Therefore, the effectiveness of the ART system can be judged based on the proximity of taxi trip origins to ART stops. The results show that the vast majority of taxi trips originated within a half mile of an ART stop. This suggests that the service provides a good degree of access for people wishing to use transit over taxi or personal vehicle use. In addition, the distance distributions do not appear to show significant differences from weekdays to weekend.

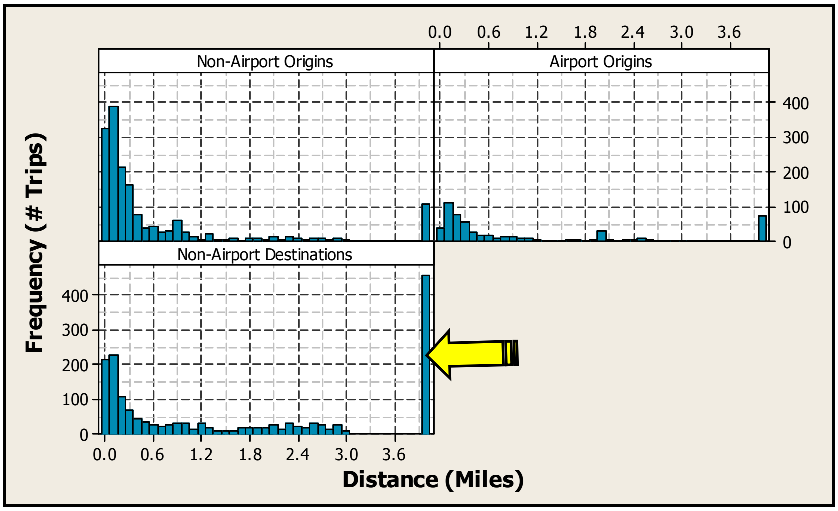


Figure 34 - Proximity of Wednesday Taxi Trips to ART Bus Stops

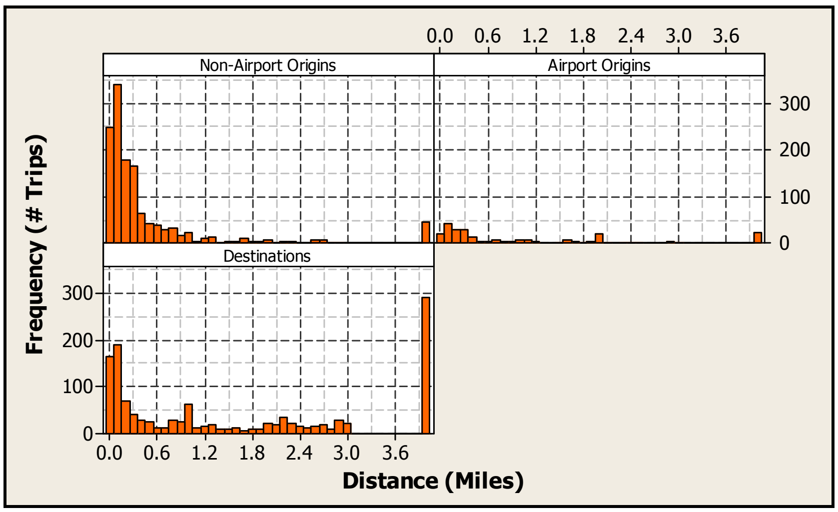


Figure 35 - Proximity of Saturday Taxi Trips to ART Bus Stops

6.1.3. Taxi and WMATA bus

The results show that virtually all taxi trip origins and destinations were within three miles of a WMATA stop. In addition, the average distance from taxi passenger pickup and drop-off points to the nearest WMATA bus stop was less than a quarter mile. From these results there are two conclusions:

1) Nearly all taxi travel is possible by WMATA bus.
2) Since access to WMATA stops is adequate for most trips, other factors, such as frequency, comfort, or travel time must be attracting users to taxi travel.

These results indicate that the coverage of the WMATA bus system offers a great deal of accessibility to Arlington's resident.

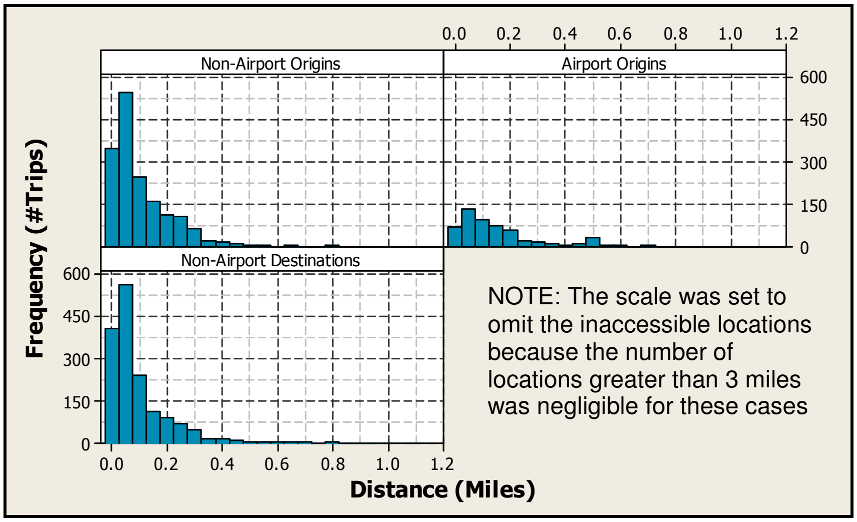


Figure 36 - Proximity of Weekday Taxi Trips to WMATA Bus Stops

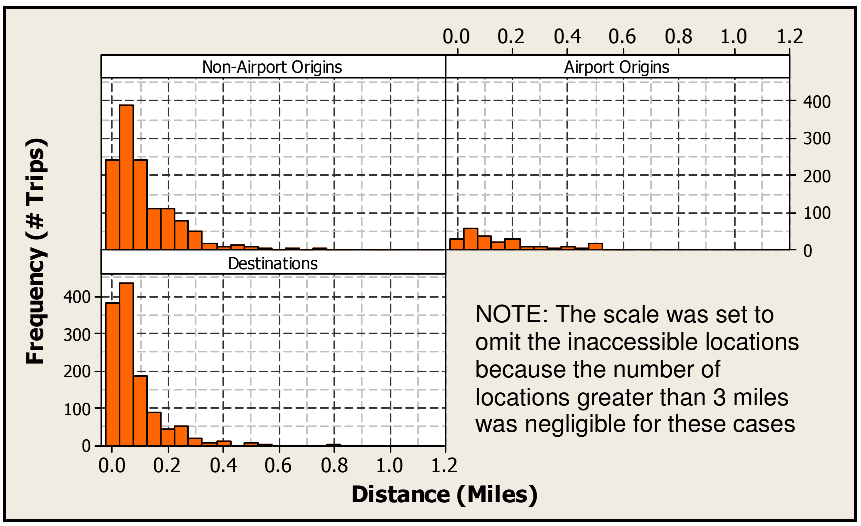


Figure 37 - Proximity of Weekend Taxi Trips to WMATA Bus Stops

6.2. Mass Transit Frequency and Taxi Travel

Although the distance to transit facilities is certainly a key factor in mode choice, service frequency is also important. Trips originating close to Metrorail stations may be explained if the headways were too long or the service was not running. However, the results do not explicitly indicate patterns that correspond to mass transit operating frequencies.

6.2.1. Defining the Parameters of Analysis

To determine the influence of operating frequencies on taxi travel, the trips in the two major Metrorail corridors were compared for different parts of the day. Because the operating headways for the Metrorail system are higher on the weekends and relatively consistent (12-15 minutes throughout the day) there were only two time periods examined: no service and regular service. During the weekday, four time periods were chosen to represent the different transit operating modes. The four time periods considered were AM peak, PM peak, Off-peak, and No Service. For the weekend analysis the regular service period was determined as the time from opening to close of service or 7:00 AM to 3:00 AM. For the weekday analysis the time periods were defined as follows:

- AM Peak: 7:00 AM to 9:00 AM
- PM Peak: 4:00 PM to 7:00 PM
- Off-Peak: 9:00 AM to 4:00 PM
  7:00 PM to 12:00 AM
  5:00 AM to 7:00 AM
- No Service: 12:00 AM to 5:00 AM

These definitions were chosen to shadow the operating schemes of the local transit providers. The 'no-service' time periods were determined based on the Metrorail operating schedule. The AM and PM peak periods were conservatively defined—the actual peak operating scheme may extend earlier or later than the times indicated. The results of the analysis are discussed in the following subsection.

6.2.2. Frequency Results

The results show that the operating schemes of transit seem to have little effect on the frequency of taxi trips. Again the reasons for this may be that there are many more trips during the peak periods than the non-peak periods. When analyzed on a per hour basis, the number of taxi trips resulted in the rates shown in Table 8. In addition, the spatial distribution of taxi trips for the time periods analyzed is presented in Figure 38 and Figure 39 for Wednesday and Saturday respectively. The results show that there is not a noticeable shift in origins or taxi trip frequency that corresponds with transit operating frequencies. However, the frequency of taxi travel was shown to be highest in the AM and PM peaks, which correspond to the peak operating times for mass transit and also vehicular peak hours. In addition, the frequency of taxi trips during the times when there is no Metrorail service is consistent between weekday and weekend days. These results further demonstrate the distributions shown in Figure 17and Figure 18 in which the taxi trips are relatively well distributed throughout the day and only a small portion appear during the late night hours when Metrorail would not be operating.

Table 8- Frequency of Taxi Trips by Time of Day

Time Period	Trips	Trips/Hour
Weekday		
AM	201	100.5
PM	244	81.3
Off-Peak	856	61.1
No Service	91	18.2
Weekend		
Regular Service	731	36.55
No Service	74	18.5

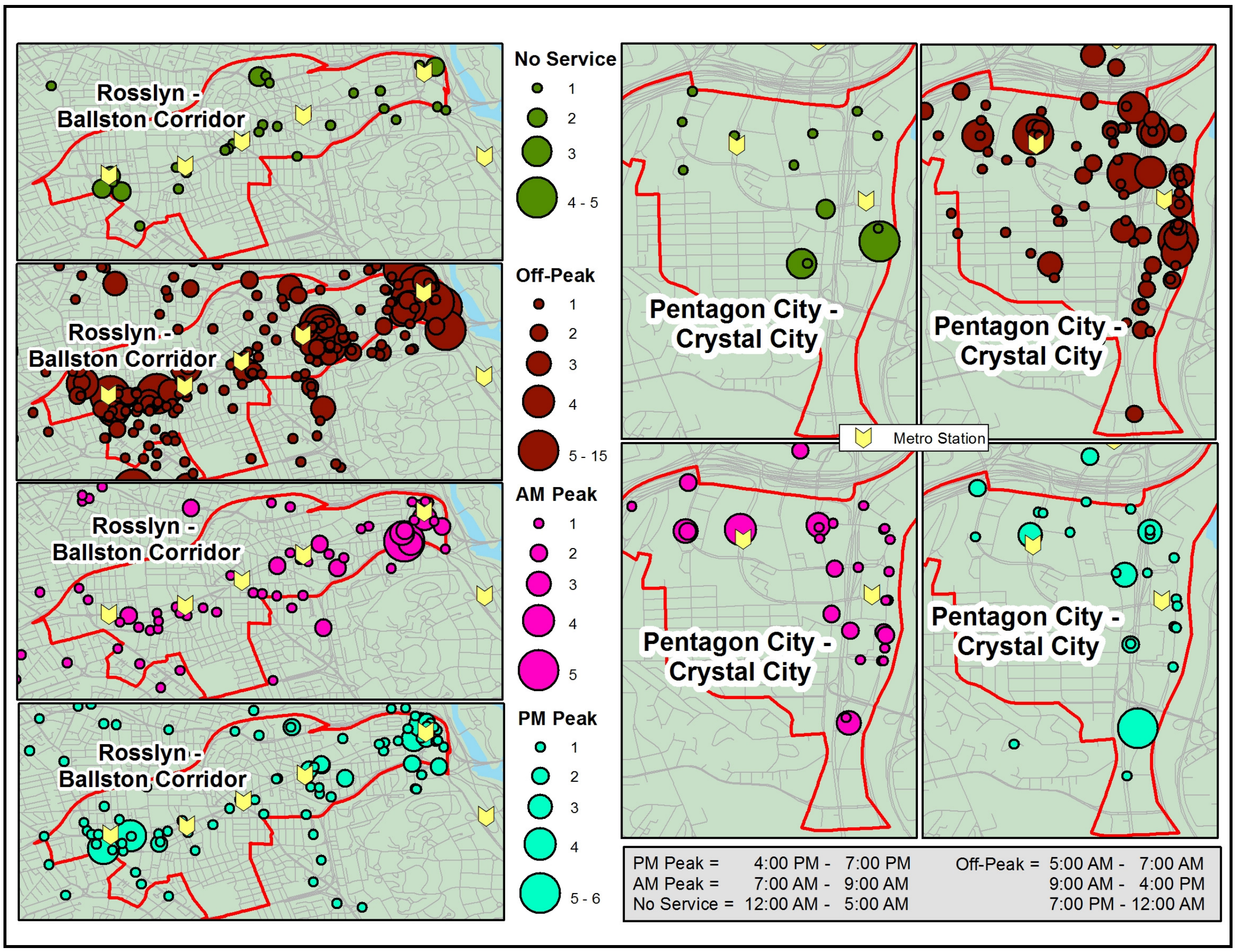


Figure 38 – Time Period of Wednesday Taxi Origins in Metrorail Corridors

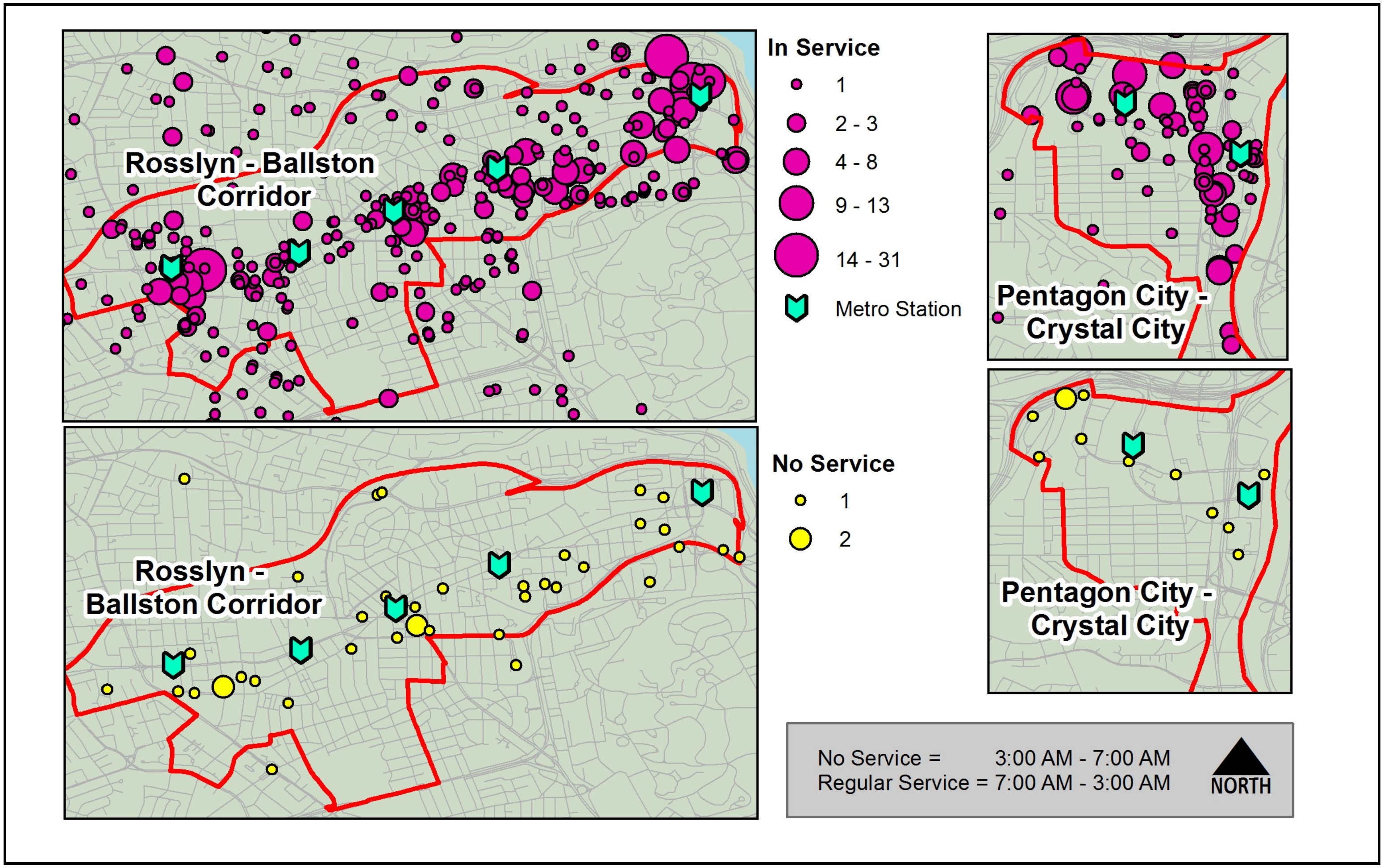


Figure 39 – Time Period of Weekend Taxi Origins in Metrorail Corridors

6.3. *Taxi Travel and Mass Transit Efficiency*

Another important aspect of taxi travel to consider is how well the mode compares to other forms of mass transit on an efficiency basis. This comparison is not purely academic due to the taxi's growing use as a form of public transport for various uses as discussed earlier.

6.3.1. Vehicle Utilization

The vehicle efficiency outlined in section 5.6.2 was a percentage occupancy factor for the taxi trip data analyzed. To compare this to other modes of transportation, operational data must be available. The NTD provides many descriptive statistics regarding transit operations nationwide. Data from the NTD combined with data from the regional providers allowed for a vehicle utilization factor to be developed. The table below summarizes the results of comparing the total passenger miles to the total seat miles for the major transit systems in this paper. The specific assumptions used to calculate these numbers were discussed in the Methods section of this paper.

The results show that taxi actually has a higher vehicle utilization factor than the other modes. This simply means that the ratio of passenger miles to seat miles is higher in the taxi. Intuitively, this is logical, since a taxi traveling one mile incurs 4 seat miles but a bus travel one mile incurs 65 empty seat miles. Only when we consider energy consumption can a comparison on true efficiency be completed. Surprisingly, the Metrorail service provides the poorest utilization of vehicles. It should be noted that the total vehicle miles used in the calculation includes all miles traveled rather than the number of miles in service.

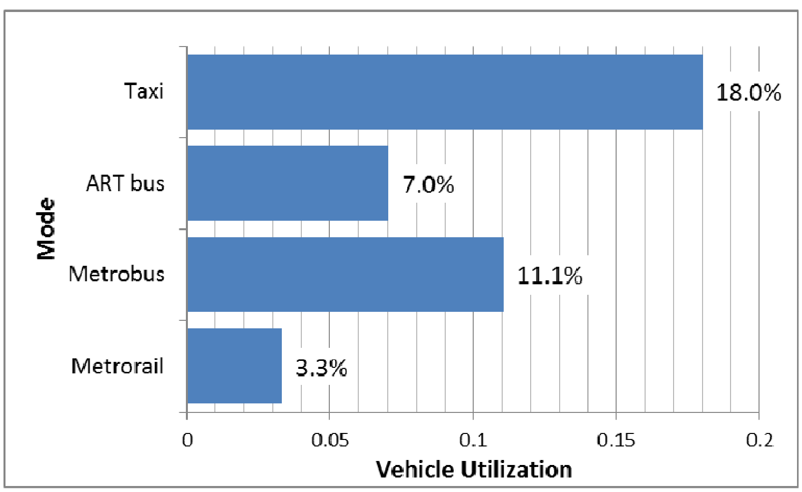


Figure 40 - Vehicle Utilization Rates for Different Modes of Transit

6.3.2. Energy Efficiency

The results of the sampled manifests show that taxis are competitive with other forms of public transportation when evaluated on an energy consumption basis. Table 9 compares the calculated taxi energy consumption based on the sample week in April of

2010. The total passenger-miles for the taxi mode was calculated based on the total miles provided for each sample day multiplied by the average occupancy factors for the sampled weekend and weekday. Saturday and Sunday were considered weekend days for the purpose of this calculation and the average occupancy on Friday was estimated as an average of the weekday occupancy and the weekend occupancy. The results from the taxi calculations are compared to data from the NTD for several other public transit modes. Energy consumptions were converted based on the values in Table 1 from the US Department of Energy.

Table 9 - Energy Efficiency Comparison of Taxi and Other Public Transit Modes

Mode Type	Passenger-Miles	GGE Consumed	Ratio
Taxi (Sample Week Total - 04/2010)	196,691	12,009	**16**
ART Bus (Annual - 2010)	3,383,683	277,242	**12**
WMATA Metrobus (Annual - 2010)	394,906,087	12,388,958	**32**
WMATA Metrorail (Annual - 2010)	1,635,967,269	14,598,892	**112**
WMATA Para-transit (non-taxi) (Annual-2010)	16,532,675	3,663,554	**5**
Arlington Para-transit (non-taxi) (Annual-2010)	255,354	74,938	**3**

NOTES:

1. Taxi GGE based on estimated fuel economy of 26 mpg. 26 mpg was chosen according to the Arlington Taxi Ordinance requirement for all new cabs effective in June of 2010. This value was also found to be comparable to the average passenger car fuel economy in 1980 according to the Bureau of Labor Statistics. This assumption was considered conservative since Arlington has a high percentage of hybrids.

2. Energy Conversions According to Table 1, from DOE.

3. Transit Data taken from the 2010 National Transit Database, FTA, http://www.ntdprogram.gov/ntdprogram/

4. Para-transit figures do not include contracted taxis for demand responsive services.

Although Table 9 shows the results of the energy consumption comparison, it is important not to conclude that Mode X is "better" than Mode Y. Each mode serves a slightly different purpose in the greater transportation network. Therefore these purposes should be considered in any comparisons. The results show that Metrorail travel is the most fuel-efficient transit of the modes examined; WMATA bus service is the second most efficient, and ART bus service is the third. Although these modes have differing fuel consumption efficiencies, they serve different purposes. ART bus service mainly serves as a collector bus to funnel residents from less densely-populated areas to the Metrorail Stations and CBDs. Given its function, more empty seats are likely on ART routes and thus, less efficient vehicle movements can be expected. However, without the routes provided by ART, many of Arlington's residents would be isolated from transit and unable to reach the Metrorail or bus routes. Likewise WMATA buses service a much broad area than the Metrorail system and are likely to experience the same effects as the ART buses. However, since WMATA buses typically travel along arterial routes with more densely populated areas, the buses are more likely to have a consistently higher demand than ART.

According to the results, taxis have an advantage over the ART bus service and the two paratransit services in the area of fuel consumption. However, it is not possible to directly substitute taxi service for paratransit services if the vehicle is not wheelchair accessible. In addition, the ART bus service also accommodates bicycles and wheelchairs, which taxis may not. The results do support the notion that it may be more efficient for taxis to service demand-responsive paratransit services and even some fixed route applications. In fact, both Arlington and WMATA already contract with taxis to provide demand responsive services. According to the NTD, taxi contracted trips accounted for approximately 14 percent of the total paratransit passenger miles provided by WMATA and 45 percent of those provided by Arlington.

6.4. Summary

Although there is a relationship between taxi travel and mass transit use, the data do not clearly show the influence of transit option availability on taxi use. The frequency and location of taxi trips appears dependent on the land use rather than the attractiveness of nearby transit options. Taxi trips were generally close to WMATA stops, while taxi trip destinations were generally not accessible by ART. The operating data of the mass transit modes present in the area support the research performed by others that suggests taxis are an efficient means of transport.

7. Planning Applications for Taxi Data

Although analyzing taxi travel can certainly offer the opportunity to improve the taxi service provided to the public users, the opportunity for planners to utilize this readily available data source for other applications is also critical. Taxis should be considered independent data gatherers for the jurisdictions they service, constantly collecting useful travel surveys. Taxi travel data can tell planners about the critical questions in transportation: where, why, and how? The data from a taxicab shows the actual cost, path, origin, and destination of a trip. This type of data is normally not available to planners or engineers, and thus planners may pay for data from Bluetooth devices, license plate surveys, or travel surveys. By utilizing taxi data, planners can more accurately calibrate many of the models used in travel demand forecasting and long range planning. This section will discuss the possible utilization of taxi data for planning purposes, and proposes a possible workflow for agencies to follow.

This thesis has explored the use of the data in analyzing operations and relating the taxi to mass transit, but the opportunity to analyze transportation services provided is much broader. The data collected from taxis has instant applications for taxi policy and planning. A few examples of applications are discussed in the following section. It is important to note that taxi companies can also benefit from robust electronic data in analyzing their operations and optimizing dispatches. In addition, the newer forms of data management can streamline the connection between regulators and taxi companies, reducing paperwork and time for both.

7.1. Data Flow Process

The process presented in the flowchart in Figure 42 is an example of how data from taxis are able to support a variety of agency decisions. The data are shared with agencies and in turn the agencies gain insight into taxi operations and user demand. By utilizing these data the agency can in turn provide better support for taxis and other public transportation. Figure 42 shows how standard taxi data can be combined with agency data, such as land use, demographics, and population to perform a variety of analyses from taxi stand capacity to taxi trip demand modeling. These analyses can be used to make a variety of decisions. The decisions included in Figure 42 span the areas of taxi operations, transit planning and general transportation planning. The wide range of applicable transportation decisions should provide motivation for agencies to pursue improved taxi data. There are a few key areas of discussion that this section will focus on: data acquisition, data sharing, and implementation.

7.1.1. Data Acquisition

The data are originally acquired from two sources: the individual taxis and the taxi company dispatch system. The data from the taxis are compiled with Mobile Data Terminals (MDT) and GPS tracking within the taxi itself. This assumes that the company has GPS and a type of MDT. In reality, many smaller companies do not have sophisticated MDT and dispatch systems yet. However, with the increase in mobile technologies a wide variety of scalable systems are arriving on the market. This means that regulations requiring electronic data may not necessarily unfairly burden smaller companies. Another potential benefit of this data flow process is that the hail trips are better captured by the electronic record keeping methods as the driver does not need to manually enter the data in a hurried situation.

7.1.2. Data Sharing

The critical missing links in the process are between the taxi company servers and the agency servers. Currently, most regulators or agencies do not have real-time access to taxi positions or status. Real-time data may not be as necessary from an agency standpoint; however, recorded daily movements would be useful for agency planning. Therefore, although no direct access to taxi company dispatch systems is needed, agencies need to have access to the electronic data from the MDTs and the user wait times from the dispatch software. Ideally, the agency will operate a server where various taxi companies can upload their data. Eventually, if public wi-fi is added to transit stops, this transfer of data could be triggered when a cab travels within a network signal area.

7.1.3. Implementation

Although the numerous possible applications for taxi data are appealing, they cannot be realized if the political barriers that prevent agencies from accessing the data are not overcome. The key barriers in most cities today that prevent the flow of data between taxi service providers and agency databases are a lack of technology (primarily due to cost) and political and privacy concerns.

The technology required for computerized dispatch and electronic data collection are more widely available today, but they also may be costly and require significant initial investment. Smaller companies may especially be disproportionately overburdened. To combat this threat, many mobile technologies are being developed that allow for scalable dispatch systems. These systems rely more on smartphone technology and are less costly initially. Smaller companies could begin by using these types of systems to keep capital costs lower. Agencies could also support taxi providers by offering discounted licensing fees or inspection fees for companies that submit data electronically. A more aggressive approach from agencies could use detailed audits of manual manifests to require companies to switch to electronic data if the error rates are unacceptable or the data are unusable. Additionally, there are probable cost savings to taxi operators as the amount of paperwork will decrease and the regulatory checks can be completed more efficiently. These savings could be used to justify the initial outlay for improved technology.

Political barriers are also a real threat to improved data. Drivers may feel that they are being monitored or unfairly scrutinized. However, the distraction and hassle of filling out manual manifests is removed from the driver and may improve their overall job satisfaction. Also, agreements could be made to assuage the driver concerns about off-duty monitoring. From the user side, more accurate data should serve to protect the users from fraud and fare rejections as well. Another major issue may be privacy concerns from both the taxi companies and the users. Taxi companies may not want their competition to see which market areas they are targeting and where their loyal customers are located. One approach to combating these concerns is to take steps to secure and anonymize the data. For example, agency servers would be secure and data would be anonymized with respect to individual addresses when performing analyses. Another approach would simply follow the logic that any trip provided is public record in a regulated environment and would not take steps to protect company proprietary data or user addresses.

To implement a shared system of data exchange one thing is clear: public agencies and public service providers must mutually pursue a common goal. Although the agency may find ways to require private companies to comply with their requests, voluntary commitment from the private sector is always preferable. Another benefit to improved data is that Flexible Transport Services may be developed more easily with taxi providers as a key stakeholder. An environment of cooperative advancement could go a long way in creating smarter more agile taxi service and innovative forms of paratransit.

7.2. Examples of Data Applications

Although all of the applications listed in Figure 42 are not discussed in detail in this thesis, some are explained in more detail in this section.

7.2.1. Stand Analysis

In urban areas, such as Arlington's CBD, on-street parking is often a scarce commodity and competes directly and fiercely for curb space with taxi stands and transit stops. By utilizing the recorded locations of taxi fleets throughout a day, planners can determine which stands are being used, when they are being used, and for how long a cab is waiting. To accomplish this, planners can harvest recorded GPS data from the taxi companies and use a script running in a GIS to generate entry and exit times for taxis at a stand. The stand can be delineated within GIS using a simple polygon as a capture area, much the same way that video detection is used for traffic signals. In this way, planners can analyze stand location and capacity. Furthermore, if there is an area that planners think may warrant a stand, the capture area can be shifted on-street to capture the number of loitering cabs and estimate demand. Adding GPS data from transit operations can also aid in allocating curb space and detecting conflicts in the flow of buses and taxis. Figure 41 shows a schematic example of this type of stand capacity analysis. This type of analysis is only one example of the many potential applications that agency planners using taxi data could pursue.

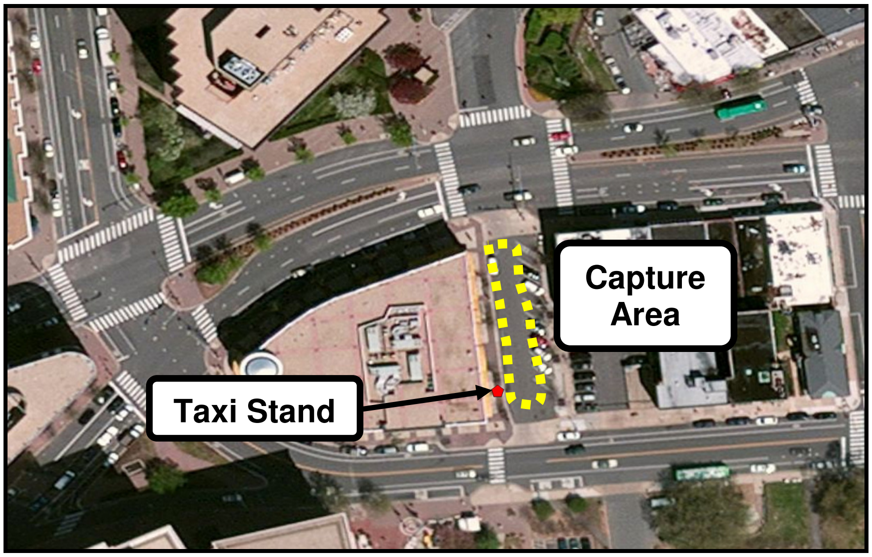


Figure 41 - Example Stand Monitoring Capture Area

7.2.2. Taxi Policy Impacts

Regional taxi service optimization could also be aided by taxi data from multiple jurisdictions. In the Arlington area for example, the taxi trips provided across the Potomac often result in an empty vehicle returning to Arlington or DC. By utilizing GPS movements and electronic fare data, regional models can be developed and the impact of policy changes can be estimated more accurately. For example, a fare increase in Arlington may result in more taxi users attempting to use DC companies to exit the district while a fare increase in DC may encourage DC-based taxis to accept more fares to Virginia or outlying areas. These types of analyses are only possible if there is a regional consensus on data management.

7.2.3. Transportation Planning Applications

Some of the applications for taxi data in taxi planning were discussed in the literature review at the start of this paper. However, there are several other interesting analyses that could arise from studying taxi data. For example, using taxi data to calibrate the attraction and generation potentials of different land use could be useful in developing accurate travel forecasts. Furthermore, taxi data could be used to plan additional functions for taxis in ancillary transit forms. Planners could determine average wait times and decide whether using taxis for non-emergency 911 responses would provide adequate savings and service. Another interesting application of taxi data would involve connecting taxis to the ever-expanding bicycling community. The addition of the Capital Bikeshare program has dramatically encouraged the use of bicycles throughout Arlington and DC. Planners could use taxi data to determine whether providing bicycle accommodations on cabs (bike racks) might provide further connectivity.

7.2.3.1. Applications of Origin-Destination Tables

The resulting Origin-Destination tables can quickly identify non-compliant travel and even erroneous data. Planners could utilize OD tables such as these to quickly perform compliance checks for the taxi travel. For example, in Table 4 and Table 5, the rows and columns highlighted in green represent all of the zones in Arlington. Any trips recorded outside of these green bands are violations in that they do not originate or terminate within Arlington (the exception being trips to Loudoun County, which includes IAD). It is clear that using geo-referenced taxi data can help regulators quickly check the rates of violations, but the applications of the OD tables go beyond simple code enforcement.

In addition to compliance, planners can instantly create and tailor their own OD tables to calibrate models used for forecasting or demand modeling. Regulators also have access to data that ties individual addresses to specific land use types. By utilizing the taxi data, planners can use the land use data to check trip generation rates, the effects of stand locations, or a host of other topics.

7.2.4. Transit Planning and Operations

The continuous monitoring of taxi travel data could be used to calibrate transit routes. Planners could examine the areas within a certain distance of bus stops to see if there is a spike throughout the day in taxi trips. A higher rate of taxi trips throughout the day could indicate the need for increased transit frequency. The same concept could apply to the routes of transit. Although this thesis found manual data too narrow to observe a shift in taxi trip demand, more detailed electronic data may provide better insight. In addition, the analysis of taxi trip duration and distance could be used to identify areas of congestion that require improvements such as changes to signal timings.

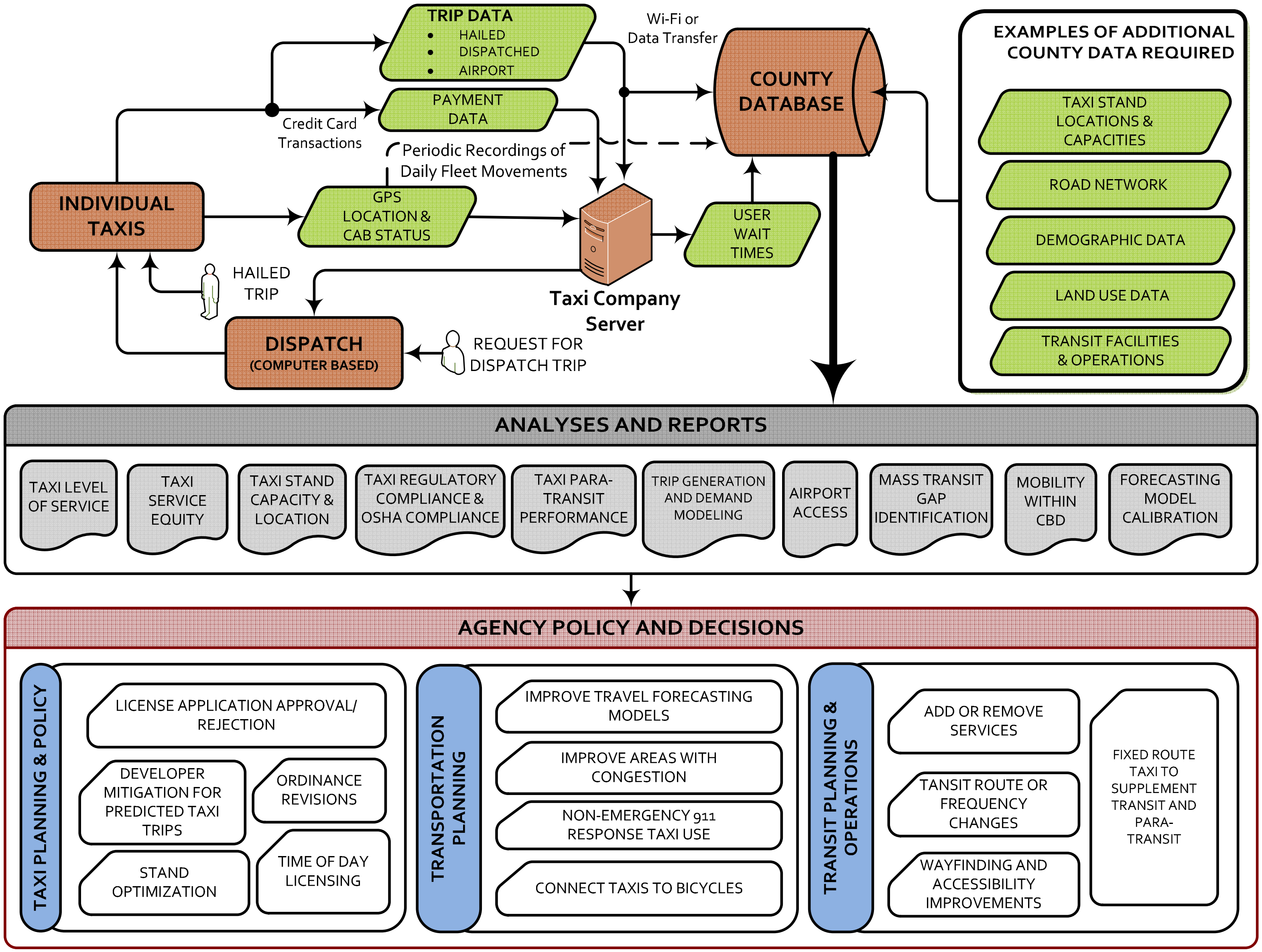


Figure 42 - Taxi Trip Data Flow for Agency Planning

8. Conclusions

The results confirmed the ancillary hypotheses posited at the beginning of this thesis. However, the main objective of identifying shifts in taxi travel due to transit systems was less successful. The results do not show observed spatial variation for different operating frequencies. In addition, the taxi trip frequency did not increase with distance to transit facilities; instead, the majority of taxi trips occur in the areas immediately adjacent to transit facilities. This suggests that other variables such as land use, vehicle ownership, and population density are the prevailing factors for taxi trip generation. Still, from the research conducted in this thesis there are several areas that provide useful lessons and results for moving forward in the area of taxi transportation.

8.1. Effectiveness of Taxi Travel Data

Examining taxi data can potentially provide valuable insight into the operational characteristics of taxis in urban transport. Visualizing taxi trips in two-dimensions is helpful in examining the spatial relationships of taxi trips to land use and transit. However, adding a temporal component through animation or a three dimensional plot could provide even further insight. The various relationships between taxi travel parameters are available to regulators through taxi data and can help describe the state of the industry while providing empirical data on which agency decisions can be based. Unfortunately, the quality and availability of data are limiting factors.

This thesis found that a large percentage of the taxi manifests were flawed. In addition, there were difficulties determining the time of the trips as military time was often not utilized. Finally, the format of the manifests does not emphasize the town or city and thus many drivers omitted this information for areas outside Arlington. Although changes to the manifest formatting may reduce some of these errors, electronic data could go a long way in allowing for more detailed analysis and should be prioritized. In addition, electronic data would free drivers from the burden of manual data entry and speed regulatory compliance checks as demonstrated by the ease of generating the OD tables presented in the earlier sections.

8.2. Travel Characteristics

Examining the manifests provided insight into how the taxis are functioning within the urban-suburban context. The point of this thesis was not only the results, but how they were generated, because the data used are common, fixtures in a regulated environment.

The results show that taxi trips in Arlington are generally short in distance and duration and therefore, most trips are below $20 in cost to the user. The vast majority of the taxi travel in Arlington took place in the two Metrorail corridors. This confirms the link between taxis and transit and supports the notion that TOD also requires well functioning taxi service. The results also highlight certain special destinations such as hospitals, rail terminals, and major employment centers such as the Pentagon. Surprisingly, the average speed of taxi travel was calculated as only 18 mph, which is not as fast as the average travel speed reported by the Metrorail system. Travel speed is deceptive however, as access time differs from transit to taxi.

8.2.1. Day of the Week Variation

As expected, the results show that weekend taxi travel and weekday taxi travel are inherently different. This thesis found that the fare, distance, and especially occupancy of taxi trips differ between weekday and weekend travel. Surprisingly, a greater percentage of the taxi trips traveled from Arlington to DC on the weekend as compared to the weekday analyzed. This suggests that although the percentage of taxi trips within Arlington is significant, the influence of DC as an employment destination is not as central as one might think—at least as far as taxi travel is concerned.

8.2.2. Airport Travel

Contrary to other trip purposes, airport taxi travel was found to be steady throughout the week, as the average distances, fares, and occupancy were not significantly different. However, the results show that the airport access trips are generally more expensive and have a lower occupancy than taxi trips for other purposes. The majority of the taxi trips to the airport were concentrated within the Metrorail corridors, but the demand pattern was much more dispersed than that of non-airport travel. The low occupancy of airport taxi travel suggests that there is opportunity for agencies to provide FTS that attempts to boost occupancy based on a different operating scheme.

8.2.3. Transit Relations

Generally, taxi trip rates appear to be almost independent of distance to transit facilities or operating schemes of transit. When transit is not available, users would likely travel by taxi, yet there is not a large spike evident in taxi travel during these times. Instead, taxi travel seems to be concentrated around existing rail infrastructure suggesting that taxi trip rates are most likely influenced by population density, land use, and vehicle ownership. However, there are hints in the data that show slight shifts in the distribution of taxi trips towards transit during the weekend. This suggests that there may be an influence, but it is not easily observable for the given sample.

It was possible to estimate several indications of the efficiency of taxi travel by compiling the manifest data and comparing to transit figures. The results show that the taxi operations in Arlington generally utilize their vehicles well. Additionally, taxi travel was competitive on an estimated energy efficiency basis, consuming less energy per mile than non-taxi paratransit and local bus services. However, agencies could not simply substitute taxis for these roles because there are prohibitive vehicle requirements. Still, the exercise of examining vehicle and energy efficiencies is one that could be repeated in other jurisdictions to help identify areas where taxis could be used to supplement traditional transit.

8.3. Applications for Agency Planners

This thesis shows that the taxi data collected on manifests can be utilized to conduct spatial analysis and also for examining taxi trip characteristics. In addition, some of the proposed uses presented in this thesis are outlined in the presented data flowchart in

Figure 42. These applications include areas of taxi operations, transit, and transportation planning. Although there are anticipated barriers to implementing such a data flow, agency and private cooperation should be able to mitigate the concerns to allow for improved data management. Some of the various suggested applications for taxi data that were summarized in Figure 42 are:

- Taxi Level of Service
- Taxi Service Equity
- Taxi Stand Locations and Capacity
- Taxi Regulation & Labor Regulation
- Paratransit Performance
- Taxi Trip Generation Rates & Demand Modeling
- Travel Pattern Analysis (OD tables)
- Measures of Mobility (effect of delay on fare)
- Forecasting Model Calibration
- Transit Gap Identification

These different applications can be used to support a variety of agency decisions. In the United States, taxis are being deployed for an ever-increasing set of uses. To support these new roles and more clearly define the taxis role, data collection techniques need to improve based on time saving technology and substantial data sharing must also follow.

8.4. Further Research

The results achieved in this thesis are indicative of the limitations of manual taxi data. Identifying gaps in transit requires more accurate and more frequent data samples. Further research utilizing many days of taxi data and specific individual transit routes should be conducted to see if identifying gaps in mass transit is practical given robust electronic taxi data. A particular method for analyzing the movement of taxis in a capture area should also be developed for a GIS environment.

The amount of research into taxi use for non-traditional uses is rapidly expanding. Research into whether taxis can fulfill these expanded roles to the satisfaction of the users should be conducted regularly. In addition, the energy consumption of taxis appears to be competitive to local collector bus service according to this research. However, the ART system analyzed in this research is relatively new (started in 1998) and may not have reached its full ridership potential. Research into the use of taxis in supplementing local bus routes, especially during off-peak times, should be further developed in the United States. The taxibus is already popular in many other countries, but the concept has not been as common in the US.

Finally, because multiple taxi companies may begin to provide additional functionality for agencies, a centralized dispatch for contracted paratransit trips may eventually become necessary to improve customer service and to provide for fair competition between service providers.

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