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STUDY OF THE TRADE-OFF BETWEEN EFFICIENCY AND EQUITY IN THE CONTROL OF URBAN TRAFFIC NETWORKS

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ABSTRACT

Congestion in urban traffic networks has become a recurring issue that continues to escalate to unprecedented levels of concern. Network-wide traffic control techniques offer a viable, realistic, and universally applicable solution to mitigate congestion. One particular network-wide technique to manage traffic is perimeter flow control, otherwise known as perimeter metering. Perimeter metering is effective because it is cheaper than building new infrastructure and does not require new traffic control policies. Perimeter metering is simply implemented by re-timing existing traffic signals along the perimeter of an urban network. One drawback to perimeter metering is that it is inherently inequitable. Specifically, it causes a subset of the travelers using a network to experience higher average delays than other travelers. With that inequity taken into consideration, a perimeter metering strategy still offers a viable solution to mitigate congestion as it results in a more efficient traffic network overall. This thesis explores the trade-off that exists between improving the overall efficiency of a traffic network while introducing a geographical inequity when perimeter metering strategies are incorporated into an urban traffic network. Comparison of travel times for those traveling from a suburb to the downtown with downtown only travel times revealed a non-linear relationship between the inequity and inefficiency introduced from incorporating variations of two different perimeter metering strategies. This thesis discusses the assumptions, traffic dynamics, and metering strategies in detail. Finally, it compares this trade-off using measures such as elasticity to understand ways in which a perimeter metering strategy could be applicable within an urban traffic network.

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Chapter 1

Introduction

Background

Congestion within urban traffic networks is a substantial problem. For example, during 2011, United States citizens that lived in urban areas wasted approximately 5.5 billion hours while stuck in congestion (Schrank et al., 2012). Congestion does not only cause an inconvenience with regards to travel time, but it also is costly to the travelers and to the environment. It is estimated that congestion within urban areas came at a cost of approximately $121 billion in 2011, which, to put in perspective, is greater than the total gross domestic product of Puerto Rico (Schrank et al., 2012; The World Bank, "Puerto Rico"). Furthermore, it is estimated that an additional 56 billion pounds of carbon dioxide were released into the environment from vehicles within urban traffic networks because of the wasted 2.9 billion gallons of gas due to congestion (Schrank et al., 2012). To put these figures into perspective, each traveler disburses about 380 pounds of carbon dioxide annually and the amount of wasted gas could fill the Mercedes-Benz Superdome in New Orleans, Louisiana, four times over (GWU, "Traffic Offenses: What Road Congestion Does to Our Air").

The most concerning challenge related to congestion in urban traffic networks is the rate at which congestion has grown and is projected to grow in the future. The inflated cost of congestion increased by nearly 4 times between 1982 and 2000 (from $24 billion to $94 billion). The total delay experienced by urban travelers, due to congestion, during peak travel times has more than doubled from an extra 16 hours in 1982 to an extra 38 hours in 2011 (Schrank et al., 2012). Accumulated over a year, this 38 hours in delay is nearly equivalent to the driving time required to make the 2,800 mile journey from Washington D.C. to San Francisco, California (Johnson, "How Long Does It Take for a Road Trip Across America?").

It is estimated that in 2020, the cost of congestion will be approximately $199 billion, the total delay experienced by travelers in urban areas will increase to 8.4 billion hours, and approximately 4.5 billion gallons of gas will be wasted (Schrank et al., 2012).

Causes of congestion in traffic networks can be classified into two different categories: recurring and non-recurring. The primary recurring causes include inadequate capacity with current infrastructure, uncontrolled demand, and poor management of the demand. The non-recurring events include events that are not typically seen under normal operating circumstances. These events could include issues with weather, work zones, vehicle collisions, and special events (e.g., sports or concerts) (FHWA, "Traffic Congestion Causes"). Although the non-recurring events are issues that may have serious impacts on the level of congestion, it is not economically feasible to design or modify roadway infrastructure based on these because it would require significantly over-designing infrastructure, which is very costly. Similarly, adding infrastructure to eliminate recurring congestion at peak hours is wasteful, as these roadways would be underutilized at non-peak hours.

Traffic control techniques offer a viable opportunity to decrease recurring congestion experienced within urban traffic networks by helping to maximize the use of available resources. These techniques could include installing more traffic signals to manage vehicle movement within an urban network, implementing Intelligent Transportation Systems, or some other type of control policy. These traffic control techniques could be integrated into an urban traffic network to help relieve existing or expected congestion; otherwise, there would be no need to add traffic control techniques in the first place. But, a significant drawback in applying some of these traffic control techniques is that they may be inequitable to a portion of their users. This inequity could be attributed to increased delay to one subset of users while another benefits or a more costly trip for some without an associated reduction in total delay. In other words, a traffic control technique may only be able to help relieve congestion for a large percentage of its users and we must understand what happens to the smaller percentage that does not experience any benefit. Ultimately, this strategy may be okay if it will reduce the overall congestion within an urban traffic network, making the system more efficient as a whole. But, in decreasing the congestion for many travelers, a portion of the travelers may be disadvantaged, which would induce a level of inconvenience that makes the traffic control strategy unfair. An agency should consider this trade-off between overall efficiency and any inequity induced when deciding whether or not to implement a specific control strategy, or how to fine-tune this strategy to provide the best balance between these two objectives.

Traffic control can be implemented at any scale. It could be effective to incorporate a technique for one specific intersection, an entire town, or across a metropolitan region. In this particular study, it is of interest to understand how a traffic control technique can affect the traffic dynamics within a large, generic urban region. This macroscopic view of a generic region was chosen primarily because of the availability of resources to generalize a traffic flow pattern experienced in urban networks. It would not be practical to study the effectiveness of a traffic control technique at a specific intersection in a specific town because the conditions to which these techniques were applied may vary significantly from one region to the next, and thus, the results may not be generalizable. Furthermore, a large amount of research has been performed in understanding the traffic dynamics within large-scale, urban environments. Therefore, to optimize the applicability of this study, a macroscopic view of the traffic dynamics will be used to understand the effectiveness of a network-wide traffic control strategy.

When referring to the effectiveness of a traffic control technique previously, efficiency and equity were briefly discussed. Although these two terms are commonly applied to many different fields of study, it is important to understand the two terms. Efficiency can be defined as generating a process or system which optimizes the net output of the system while limiting wasted resources. Equity can be defined as a process or system operating under the condition that, regardless of the net output, the users of the system maintain a significant level of comfort and are treated equally. In this particular case, the system referenced in the definitions is represented by the urban traffic network. But how does one measure how "optimized" an urban traffic network may be? Furthermore, how does one measure "comfort" and "satisfaction"? Although all of these terms define more qualitative feelings, a measure that universally represents these terms is the travel time that each user of a traffic network experiences. As an example, if somebody enters a tunnel and exits the tunnel without much of a delay, the system is said to be running efficiently and the user is typically satisfied. Furthermore, if somebody enters a tunnel and is delayed for an extended period of time, the opposite is true, where the user is not satisfied and the system may not be very efficient. This dissatisfaction that the user is likely feeling is based on the delay experienced. This uncontrollable user delay that was experienced could be considered inequitable if the reason for the delay is induced to improve traffic conditions elsewhere or periodic travel time savings for someone else using the tunnel.

In this study, it is of interest to understand the effect that traffic control techniques have on the overall efficiency and equity within an urban traffic network. Although several methods to control traffic flow were discussed previously, this study focuses on the effectiveness of perimeter metering strategies. The primary premise behind this type of metering is to carefully control the rate at which vehicles enter a specific area in the traffic network. This can easily be implemented by controlling the traffic signal timing on the perimeter of the network to “meter” the entrances into the downtown. These strategies were chosen because they demonstrate the most feasible strategy to actually implement in an urban environment (i.e. a metropolitan area may not be able to pay for new infrastructure or an Intelligent Transportation System). This type of strategy can also be easily studied at a macroscopic scale and has little to no dependence on the layout of the physical infrastructure in a city.

This study focuses on the nature of the trade-off between efficiency and equity that exists in implementation of perimeter metering control strategies at urban traffic networks. In this particular study, the total travel time of users in the system is investigated at a macroscopic scale, meaning that the travel times of the entire system are investigated rather than individual travel times. Thus, instead of studying the particular travel times experienced by one traveler in a system, all delays by similar travelers are aggregated to understand the types and magnitudes of delay experienced by various groups. The hope is that a better understanding of this information will provide transportation decision-makers with the appropriate tools to best mitigate congestion.

Paper Organization

This thesis is organized in the following manner: the literature review immediately follows this introduction. Within this literature review section, there are five primary areas of research discussed: modeling urban traffic networks, macroscopic models of urban traffic, metering as a large-scale network control technique, transportation equity, and assessing proposed traffic control strategies. After the literature review, there is a discussion of the background and traffic dynamic principles that much of this study was based upon. Furthermore, this section offers step-by-step instructions to which the data used in this study could be reproduced. Six different case studies were performed in this study to ensure that there is consistency in results across different demand scenarios. A discussion of the results follows the methodology section. The discussion primarily focuses on identifying the trade-off between efficiency and equity. The final section offers conclusions produced from this research and possible follow-up studies to this one.

Chapter 2

Literature Review

Modeling Urban Traffic Networks

Forecasting the effectiveness of a large-scale, network-wide traffic control technique has typically been performed using detailed and computationally intensive traffic models. Within the past 65 years, there have been significant developments and improvements to the effectiveness and intricacy of these modeling techniques. These improvements have shifted from the basic four-step model often used in the 1950s and 1960s, to disaggregate demand and network equilibrium in the 1970s and 1980s, to dynamic simulations in the 1990s and 2000s (Daganzo, 2007). The four-step model used four different processes to understand the impact that traffic would have on the overall street network based on network capacity. These processes are:

1. Trip generation
2. Trip distribution
3. Mode choice
4. Trip assignments

At the end of these four processes, data about congestion, travel times, volume/capacities, and number of trips can be calculated for the street network (Grzymski et al., "Basics of the 4 Step Transportation Model"). The issue with this four-step model is the significant number of inputs required to model the street network. These processes primarily rely on disaggregated socioeconomic data and detailed network geometries, so a very specific model is generated.

The disaggregate demand model utilizes data from individual travelers of a street network to understand typical travel behavior. This model is useful in urban planning efforts because it offers the following information:

1. Mode
2. Destination
3. Frequency
4. Time of Day

This model is useful in understanding specific information with regards to individual needs, such as the necessity in implementing more travel options for a certain geographical area in a city (TRB, "Disaggregate Travel Demand Models"). This model is not necessarily practical in understanding the traffic dynamics at a larger scale, such as within a large metropolitan region. This is because it would require a significant amount of data or a lot of assumptions that may introduce a bias into the results.

The network equilibrium model seeks to minimize congestion in a traffic network by considering traffic demands in terms of supply and demand. Supply is represented by the existing infrastructure of the traffic network and demand represents the potential users of the system. Ultimately, the model seeks equilibrium in the system. Equilibrium happens when the number of trips generated is equal to the infrastructure demand (Nagurney, 2002).

The dynamic micro-simulations used more recently are valuable in forecasting any metric with regards to multi-modal transportation networks. The generated data is very accurate, but not practical. Daganzo (2007) proposed that this is attributed primarily to:

1. Multiple inputs to the simulation are required (e.g., detailed origin-destination information for all simulated vehicles)
2. The users of a traffic network are unpredictable and irrational; their habits and choices are very difficult to predict accurately
3. Traffic networks that are oversaturated act unsystematically

Macroscopic Models of Urban Traffic

Daganzo (2007) proposed a model that would shift the focus of the traffic network simulations from predicting data based on the users of the system to a large-scale monitoring and control technique. The proposition utilized measures that were independent of the specific traffic network inputs, used in previous traffic models, to manage congestion. The primary tool to which this simulation depends on is called the macroscopic fundamental diagram (MFD). The network MFD relates the average density (or accumulation) of vehicles to the average flow of vehicles within a traffic network. A networks MFD has a distinct maximum and should generally not change as demand changes during peak and off-peak periods, as long as congestion patterns are more or less uniform (Daganzo and Geroliminis, 2008). Geroliminis and Daganzo (2008) confirmed that the MFD was able to predict the dynamic nature of accumulation within downtown San Francisco. The authors also confirmed the existence of an MFD in their experimental findings of Yokohama, Japan. They used fixed detectors, vehicle probes, and GPS data to understand the relationship between space-mean flow, density, and speed within an urban traffic network. The empirical results, as well as simulations and theory, suggest that MFD's do arise in an urban traffic network.

MFD's also help to describe the rate at which travelers can leave the network at any value of accumulation within the network. This exit rate and accumulation relationship, called the network exit function (NEF), is fundamentally important in understanding the balance between a congested and uncongested traffic network. In fact, Daganzo et al. (2011) described the NEF as a rescaling of the MFD curve based on the size of the network and length of trips.

The MFD/NEF was somewhat inspired by research on airport baggage carousels. Ghobrial et al. (1982) performed a study of airport baggage claim carousels, and were able to observe that there is a relationship between the density of passengers waiting along the frontage of the baggage claim carousel and the amount of time it took for passengers to exit with their bags. It was found that as the density of passengers increased, the amount of time to exit with bags increased. This can be attributed to the increase of accumulation found around the frontage of the baggage carousel. As the accumulation increased, one could expect that passengers would interfere with each other more often, which in turn, would slow their departures. Although this study was performed on baggage carousels at airports, similar principles apply with traffic dynamics where the rate at which vehicles exit a network is proportional to the accumulation in the network at a specific instance of time. Therefore, the network exit function, which is the direct relationship between the exit rate over a certain interval of time and the accumulation, is represented by Equation 1.

Equation 1. Relationship between Exit Rate and Accumulation

$$l(t) = f(D(t))$$

The NEF is assumed to be non-negative and unimodal (Daganzo, 2007). Furthermore, the NEF reaches a maximum exit rate at which travelers exit at one specific value of accumulation. This specific accumulation, which also happens to be the maximum value of the function, is called the critical accumulation. This critical accumulation serves as the difference between a congested and uncongested network. Any portion of the NEF that is positively sloped and is at a lower accumulation than the critical value represents an uncongested network. Any portion of the NEF that has a negative slope and is at a greater accumulation than the critical value represents a congested network. Once the network becomes congested, it begins to work itself towards a state of further congestion or gridlock unless the inflow of vehicles is controlled to alleviate some of the congestion (Daganzo, 2007). An example of an NEF is illustrated in Figure 1. This NEF represents data collected from traffic studies in Yokohama, Japan and linear extrapolation (Geroliminis and Daganzo, 2008). In this particular example, the critical accumulation is 8,271 vehicles because it represents the accumulation with the greatest exit rate. Any value of accumulation lower than the critical accumulation value of 8,271 vehicles represents an uncongested network. The negatively sloped curve at accumulations greater than 8,271 vehicles represents the path towards a state of congestion or gridlock.

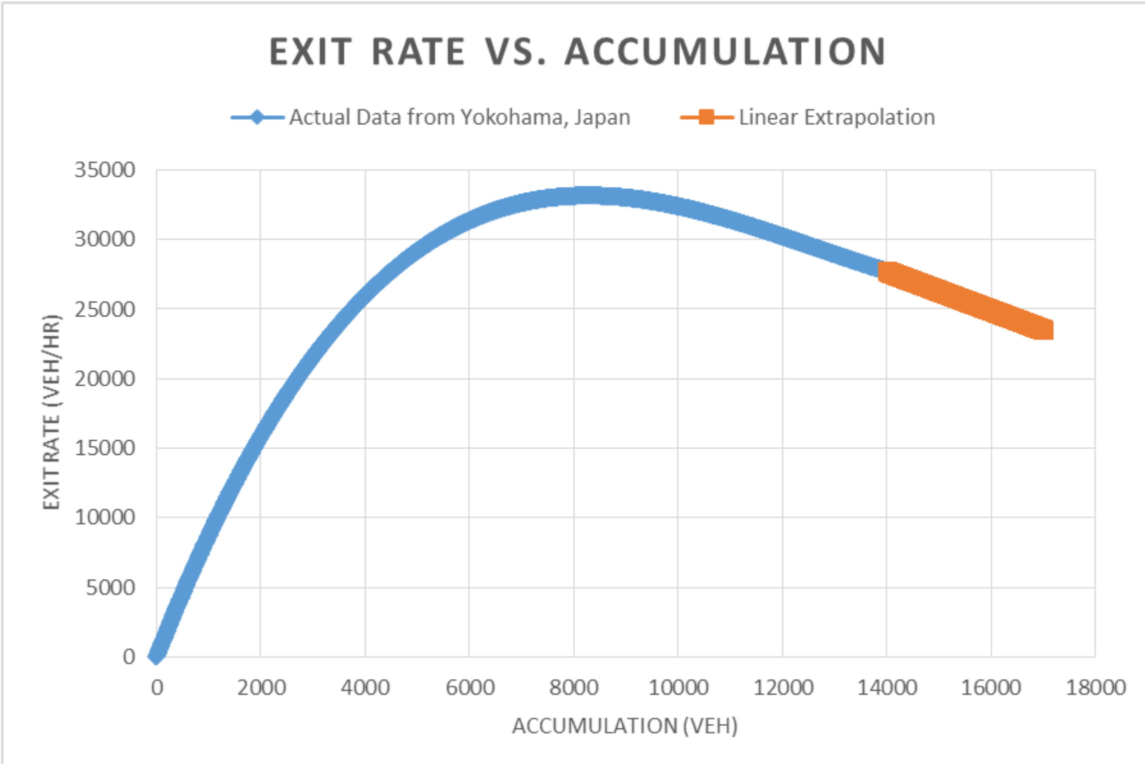


Figure 1. NEF Observed in Yokohama, Japan

Daganzo et al. (2012) proposed the possibility of using parsimonious models, like the MFD, for situations in which there is a lack of detail about a large system. They specifically suggested that in spite of individual complexities, a parsimonious model may exist as long as there are a few notable aggregate features known about a system. The benefit of using this type of model within the transportation industry is that it offers an effective strategy to understand options about how policies may affect traffic dynamics without having to develop detailed case studies. Another benefit is that it offers general insights that may be lost when using the detailed models described in the previous section (Daganzo et al., 2012).

Metering as an Optimal Strategy

The goal of implementing a perimeter control technique is to reduce the total delay experienced by the travelers entering a downtown system from a suburban area. These techniques are used at an entrance to a system; if one were to think about a boarding call for a flight, it would not make sense to control the accumulation of passengers at any time other than when the queue to board the plane initially builds. Furthermore, it is not always practical to control the demand of a system. Rather, metering techniques are used to control how demand is served. In other words, how demand is served is being managed rather than the demand itself. As an example, one can think of metering as similar to a technique that deli counters use at grocery stores. If there is not a line to place an order, one does not have to wait to place an order. When there is a large inflow of people trying to place orders at the deli counter, the employees do not turn people away because they are too busy. Rather, they manage the inflow of people wanting to place an order by providing them with a number where they can wait in the surrounding area until their number gets called by an employee. Once the first people that arrived at the deli counter get served, their numbers gets called and it is their turn to place an order.

Daganzo (2007) discussed that gradually regulating input to a traffic network is an optimal form of control to minimize congestion. Researchers used this information to help develop an efficient perimeter metering control strategy for the traffic data found in Yokohama, Japan, without significant data collection efforts, data entry, calculations, and the potential for error based on microscopic methods (Daganzo, 2007; Geroliminis & Daganzo, 2008; Daganzo et al., 2012). Their control strategy was based only on one variable that needed to be measured to be effectively implemented in practice. This variable was the vehicle accumulation within the network. The goal of the metering strategy itself was also very simplistic: keep this vehicle accumulation within the network below a critical value.

A perimeter metering strategy offers a simple and viable solution to controlling the rate at which travelers enter a network (Daganzo, "Macroscopic Fundamental Diagram and the Effect of Perimeter Control"). The perimeter metering strategy described is a different form of congestion pricing that serves to reduce traffic flow into congested traffic networks (e.g. London, Singapore, etc.). As an example, congestion pricing has been implemented to control the traffic flow into and near center-city London (VisitLondon.com, "London's Congestion Charge"). London serves as an example to illustrate the practicality of controlling the rate which travelers enter into a network, although done through pricing as opposed to another mechanism like signal control.

Keyvan-Ekbatani et al. (2014) proposed using a perimeter metering strategy, specifically remote feedback gating, to diminish congestion in urban traffic networks. Their work used traffic data from Chania, Greece, in analyzing the effectiveness of applying metering techniques upstream of the congestion. It was found that there was a 30 percent improvement in the average delay that travelers experienced in their microscopic simulation when metering techniques were applied either on the perimeter or even further upstream from the perimeter. In another study, Keyvan-Ekbatani et al. (2013) found similar results in terms of decreasing the delay that travelers in the network in Chania, Greece, experience. This study found that it is possible to achieve similar improvements with less real-time measurements for feedback gating. A drawback of this perimeter control strategy is that in order to decrease the overall delay, a subset of the travelers within the network were inherently delayed because of the gating. Because of their geographic location of being upstream of the locations where gating occurred, these travelers experienced delays that were not experienced by those that were downstream of the gating locations. Therefore, this strategy of controlling vehicles offers a viable solution to decrease the overall delay for all users, but it inherently introduces a geographical inequity for a subset of the users that are metered.

Transportation Equity

Although transportation equity has been identified as a key objective in the design process for transportation planners, the definition of transportation equity still remains somewhat subjective and involves many complications (Rock, 2012). According to Litman (2014), transportation equity is defined as the impartial sharing of transportation impacts within all sectors of society. In other words, one could define this concept of equity as attempting to eliminate any additional advantages or disadvantages of a transportation-related decision to some subset of the population. Therefore, one could consider an equitable network as one in which all users of a traffic network would experience similar conditions with regards to ease of access to the roadway network, use of the network, and price to use the network.

The Victoria Transport Policy Institute ("Equity Evaluations: Perspective and Methods for Evaluating the Equity Impacts of Transportation Decisions") suggests that there are four different types of transportation equity:

1. Egalitarianism: This system treats all users in the exact same way, regardless of their individual characteristics. These characteristics may include social class, income, mobility needs, and needs for traveling. This system thrives on ensuring that every user receives the exact same treatment and incurs the same cost with regards to using transportation infrastructure. This system is viewed as unfair and inequitable in certain aspects because it does not account as much for the social aspects of designing a transportation system. These social aspects could include, but are not limited to, income of users, needs for travel, and geographic location.
2. Horizontal Equity: This system incorporates a comparison of ability and necessity at a macroscopic scale to understand if there is justification for treating one group differently from another. Unless there is a specific reason for a difference in the way that groups are treated, all groups are treated impartially (Rock, 2012).
3. Vertical Equity with regard to Income and Social Class: This system attempts to serve disadvantaged (geographically and economically) groups with greater benefits in an attempt to balance the social inequity that currently exists. Therefore, these disadvantaged groups may be offered subsidies to minimize the cost of using a transportation network or easier access to it.
4. Vertical Equity with regard to Mobility Need and Ability: This system attempts to provide a basic level of service to all groups, but specifically focuses on offering benefits to those who may be at a disadvantage with regards to mobility and ability.

Within the transportation industry, many decisions made by planners are based around the concept of equity. Examples of these decisions, which include three described by VTPI, include:

1. Road pricing
2. Funding from government for transportation infrastructure purposes
3. Possibility of high-occupancy vehicle lanes
4. Level of service expected
5. Safety measures incorporated
6. Ease of access to the transportation network

Knowing about these decisions does not offer any particular insight into the ways in which equity can be categorized and mathematically analyzed. The Federal Highway Administration (FHWA) offers a list of categories and measurement units with regards to mathematically computing the level of equity. The categories proposed by FHWA ("Guidebook for State, Regional, and Local Governments on Addressing Potential Equity Impacts of Road Pricing") include:

1. Income
2. Geographic location
3. Demographics (race and gender)
4. Ability
5. Mode
6. Vehicle type
7. Trip type

These aforementioned categories are typically quantified with the following units:

1. Per capita
2. Per trip
3. Per vehicle mile
4. Per dollar

The measurement unit of per capita is most useful for horizontal equity analysis unless there is justification for treating one group differently from another (Litman, 2014). This is likely because evaluating per capita eliminates any dependence on income, abilities, and geographic location. One could speculate that the per dollar measurement unit would be best for the measure of vertical equity with regard to income and social class. Per trip and per vehicle mile measurement units would likely be helpful in an analysis of the vertical equity with regard to income and social class.

As previously discussed, it is extremely difficult to quantify equity, although efforts are currently ongoing. This can be attributed to the immense requirements of data analysis to quantify social variables. E.g., Shi et al. (2010) chose to use cluster analysis to quantify the benefits associated with incorporating additional public transportation options in Beijing. The authors created a linear programming model to quantify the benefit of public transportation using the following parameters: space taking, travel time, engine displacement, capacity, comfort coefficient, and benefit. Cluster analysis could be extremely useful for the comparative nature that measuring equity requires. Furthermore, measuring the travel time in which it takes vehicles to enter and exit a traffic network could be a useful gauge of the equity in a transportation network. This is because it eliminates the dependence on all variables except the geographic location. When thinking about equity within an urban traffic network, the primary variable that remains universal is the setup of the urban area itself; typically, one can find major roadways entering a downtown system from a suburb. Otherwise, variables that depend on social factors vary from city to city in wide proportions. Therefore, this measure of the total travel time could offer interesting results with regards to the equity within an urban traffic network.

Assessing Proposed Traffic Control Strategies

A traffic control strategy proposed by FHWA ("Guidebook for State, Regional, and Local Governments on Addressing Potential Equity Impacts of Road Pricing") involves the integration of high-occupancy toll lanes as an alternative to relieve congestion on non-tolled, parallel roadways. Implementing these toll lanes would allow for the users to decide on the trade-off between cost and travel time. The drawback with this proposition is the cost associated with upgrading existing infrastructure. Another proposition from FHWA is to expand the network of roads that are tolled on the local, county, and state levels. Implementing a system like this would offer a similar trade-off to the users as the proposed high-occupancy toll lanes. The drawback with this proposition is the feasibility and time it would take to implement this strategy. Another strategy to improve transportation equity includes better data collection for improved planning purposes (Litman, 2014). Other suggestions include calling for reform in terms of funding backing travel via automobile rather than other modes of transportation (Litman, 2014). These other modes of transportation could consist of public transportation and exercise-driven commuting (e.g. bike riding or walking). The drawback to this is that a mode of transportation is put at a disadvantage in terms of funding based on data that may not necessarily be representative of individual preferences.

It is typical to see that urban traffic networks often run into this issue of congestion due to the amount of travelers attempting to enter a densely populated area. Furthermore, this issue of congestion can be more prevalent at certain times during the day, such as during peak hours when many individuals would like to enter an area (e.g. morning commute to work). Gonzales and Christofa (2013) analyzed the effectiveness of the San Francisco-Oakland Bay Bridge step tolling method to control congestion. During peak hours, when more travelers would like to use this bridge, the toll price increases. The important point of mentioning this study is because it illustrates the difference between pricing and metering strategies to alleviate congestion. Pricing strategies offer options to minimize user delay by paying a certain price; the system is setup so that the traveler only pays if they want to. If the user would like to pay the price to have a shorter travel time by taking the Bay Bridge at a certain time, that is their decision. Metering strategies do not offer the opportunity to shorten travel time; some people (those metered) inherently get disadvantaged because of where they live. As an example, if a perimeter metering strategy is placed at the outside edge of a city, all of the travelers attempting to enter the city are at a disadvantage. The travelers outside of the city do not have a choice to avoid metering, which is inequitable. Therefore, it is important to see that these individuals outside of center city are treated fairly.

The idea of equity based on geographical location is the primary focus of this study. The question that will be answered in this study is: how do we balance the equity of a metering strategy on the outside edge of an urban area with the efficiency of the overall urban traffic network? Few studies have been done to understand this trade-off between efficiency and equity in an urban traffic network. Gonzales (2012) studied the trade-off between efficiency and equity with four different pricing strategies to understand how the cost differential to travelers (inequity) affected the total system cost (inefficiency). It was found that fixed pricing strategies were the most equitable because all travelers paid the same price, but the optimal time-dependent pricing strategies offered a more efficient system (Gonzales, 2012). Therefore, a trade-off exists such that one would need to choose whether it is desirable to put more emphasis on having an efficient or equitable system in terms of charging travelers who enter a traffic network. Of the studies that have investigated this trade-off, most of them have focused on pricing rather than metering strategies.

Chapter 3

Methodology

Problem Setup

The effectiveness of the perimeter metering techniques in this study are evaluated in terms of their ability to produce an efficient and equitable system for all users. The primary motivation behind optimizing a traffic network is to benefit the users. Relieving congestion would offer a reduction in travel time for users, which could offer environmental and monetary benefits.

To conceptually understand this issue with congestion, it is helpful to think about metropolis areas where congestion is most prevalent. According to Forbes (“10 Most Traffic-Congested Cities in North America”), in sprawling metropolis areas such as Los Angeles, California, and Vancouver, British Columbia, people will spend approximately 34 percent more time traveling in congestion than during off-peak times when traffic is flowing freely. Although this issue of congestion is due to both recurring and non-recurring causes, one can also think that the geographic setup of a metropolis has an impact on congestion. In thinking about a typical urban environment, there is typically a downtown area with suburban towns surrounding the downtown area. There are two sources in which trips can be generated: trips entering an urban area from the surrounding metropolitan area and trips generated within the urban area itself. Figure 2 represents this setup; the green box represents trips from the suburb and the blue box represents the trips that are occurring internally within the downtown area. These two sources of trip generation feed trips to one common destination, e.g., a downtown (orange box), where the trips will eventually end.

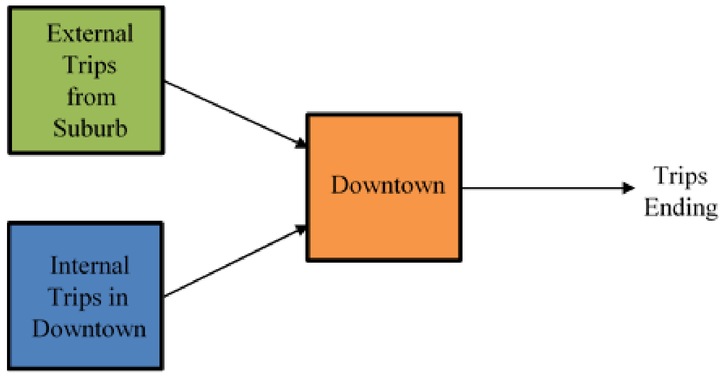


Figure 2. Schematic of Sources for Trip Generation

As an example, in the case of New York City, there are travelers entering Manhattan, a borough of New York City, New York, via 20 different bridges and tunnels from areas surrounding Manhattan (Newsday, "Map of Road Access Points into Manhattan"). Notable examples of these points of access include the Brooklyn Bridge, Lincoln Tunnel, and the George Washington Bridge. Residents of Manhattan also travel within the city limits, producing additional travelers to this downtown traffic system. Figure 3 represents the trip generation conditions in Manhattan. Although Figure 3 would vary significantly depending on the urban area under investigation, the same principles of trip generation would exist. Several points of access from the surrounding suburb exist along with trip generation within the downtown area itself.

This study will focus on how, macroscopically, perimeter metering could improve the travel time of those traveling in and around a metropolis area since this is the most prevalent area that congestion is experienced. The applicability of the results will be greater than choosing to study the traffic dynamics at a local level, such as a specific case study of New York City. Furthermore, studying how congestion could be reduced at a larger scale allows for the variability of studying individual travelers at a microscopic scale to be eliminated. Conditions that could vary include the order in which the travelers enter and exit a system, personal preference as far as time of entering a system, and driving characteristics within a system. Rather than focusing on an individual's delay, it is more representative to understand the delay that groups (e.g., several thousand travelers) experience. Therefore, the trip generation diagram for New York City (Figure 3) can be simplified to represent a generalized metropolis area as depicted in Figure 4.

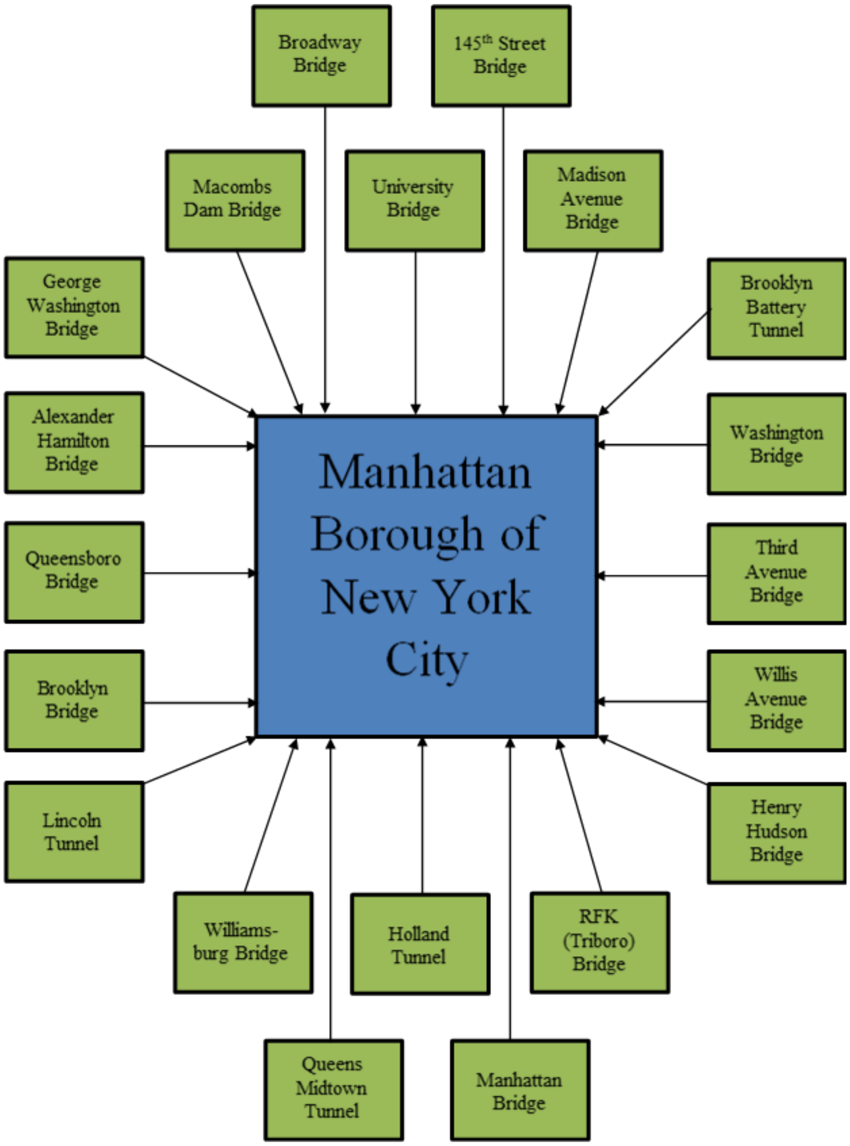


Figure 3. Sources for Trip Generation In and Around Manhattan

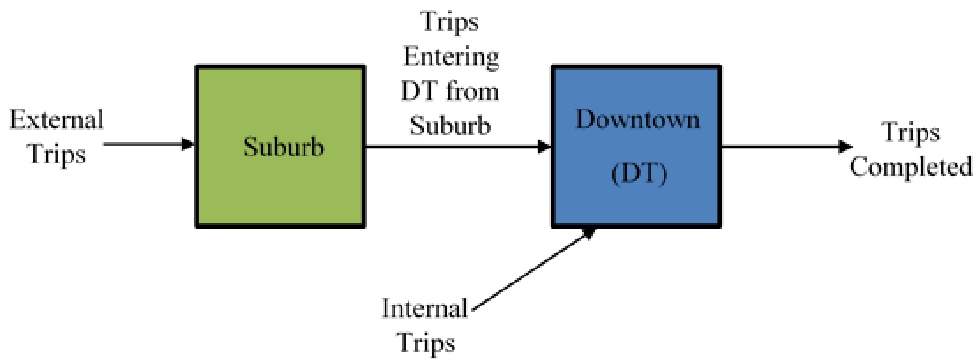


Figure 4. Network Structure for Problem Scenario

To understand the traffic dynamics associated with an urban area, the proposition from Daganzo (2007) about controlling the rate at which travelers enter a traffic network to mitigate the potential of traffic congestion will be used to create several numerical simulations. These numerical simulations will be developed using the tools previously described in Chapter 2. The goal of the numerical simulations will be to quantify the geographical inequity that exists for travelers entering a downtown area from a suburb because of metering techniques, as compared to the total efficiency of the traffic network as a whole. The inequity that may exist could be due to the fact that, although a perimeter metering strategy may reduce the level of congestion in a downtown area, it may ultimately have negative effects on those that are being metered in the first place because it is increasing their travel time to help benefit others. For example, in this study, the metering scheme reduces the total travel time experienced by downtown travelers by delaying the suburban travelers entering the downtown area. Thus, the total delay experienced by the suburban travelers only will be used as a measure of geographic inequity, as this is the amount of additional delay these users experience that downtown travelers do not. The total delay experienced by the suburban travelers will be compared to the total travel time experienced by all travelers (including those that start their trip outside the downtown area and those that start inside), which will be used as a measure of efficiency, to understand how the metering strategy effects the efficiency and geographical equity of the traffic network.

This study investigates the effectiveness of two different perimeter metering strategies to determine if a trade-off between overall network efficiency and geographic inequity exists and compare the trade-off between different metering methods. Based on the results, it will be possible to understand if there is a particular metering strategy that offers a more suitable method of reducing total travel time to the most possible users of a traffic network.

Model & System Dynamics

The idealized traffic network structure illustrated in Figure 4 was created to represent the traffic conditions found in an urban area. For the purposes of simplifying the analysis, notations were chosen to describe the key variables in this study; see Figure 5 and Table 1. As a preface to the notations described in Table 1, rates are represented by lowercase variables.

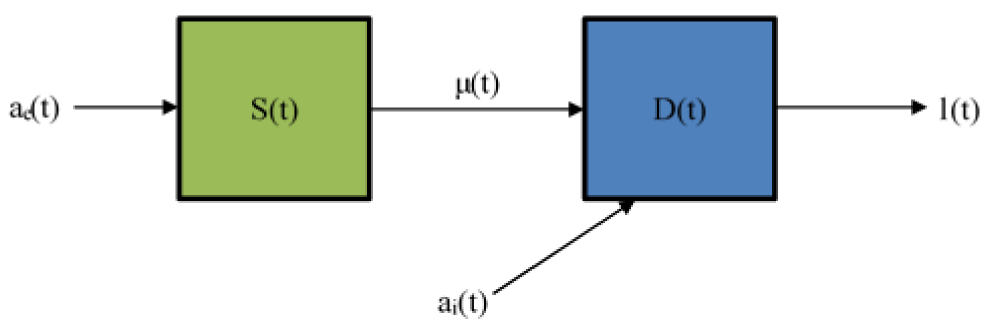


Figure 5. Notation Used for Network Structure

Table 1. Definitions of Notations Used for Network Structure

Notation	***Definition***
$a_e(t)$	Rate of external trips started by time t [veh/hr]
$A_e(t)$	Cumulative number of external trips started [veh]
$a_i(t)$	Rate of internal trips started by time t [veh/hr]

$A_i(t)$	Cumulative number of internal trips started	[veh]
μ(t)	Rate of external trips to downtown started by time t	[veh/hr]
M(t)	Cumulative number of external trips to enter the downtown	[veh]
l(t)	Rate at which trips are completed by time t	[veh/hr]
L(t)	Cumulative number of trips completed in the entire system	[veh]
S(t)	Accumulation in the suburb at time t	[veh]
D(t)	Accumulation in the downtown at time t	[veh]
C	Control Accumulation	[veh]
R	Optimal Accumulation	[veh]
Δt	Time interval of measurement period	[hr]

In order to assess efficiency and equity, one needs to understand the fundamental relationships that drive the traffic dynamics within this network. When thinking about a dynamic system, one must identify the dependencies between measures. In this case, the measures being referred to include the rate vehicles arrive to the network, both from external locations [$a_e(t)$] and internal locations [$a_i(t)$], the level of accumulation in the downtown system [D(t)], and the rate at which trips are completed [l(t)]. The two dependent variables in this study are the level of accumulation in the downtown system and the rate at which trips are completed, which are related by the network exit function. The two network arrival rates represent independent variables.

The relationship between the rate at which travelers end their trips and the accumulation has been proven to be non-negative and unimodal as explained by Daganzo (2007). The network exit function utilized in this study was based on traffic studies performed in Yokohama, Japan (Geroliminis and Daganzo, 2008). Any accumulation greater than 14,000 vehicles has been linearly extrapolated from the data found in Japan. This network exit function was chosen to simulate an actual downtown network (see Equation 2 and Figure 6). The optimal accumulation [R] of a network exit function represents the accumulation at which the maximum exit rate exists; in other words, the maximum of the function graphed in Figure 6. Therefore, the absolute maximum exit rate, *l(t)* = 33,168 veh/hr, is found at an optimal accumulation of *R* = 8,271 vehicles. Different control accumulations were tested to understand how the maximum allowable accumulation in the system affected the performance of the traffic control techniques. The control accumulation was used to trigger all perimeter metering strategies.

Equation 2. Network Exit Function (NEF)

$$l(t) = \begin{cases} 2.28 * 10^{-8} * [D(t)]^3 - 8.62 * 10^{-4} * [D(t)]^2 + 9.58 * [D(t)];\ 0 < n\ < 14{,}000\ veh. \\ 27{,}731 - 1.4 * [14{,}000 - D(t)]; otherwise \end{cases}$$

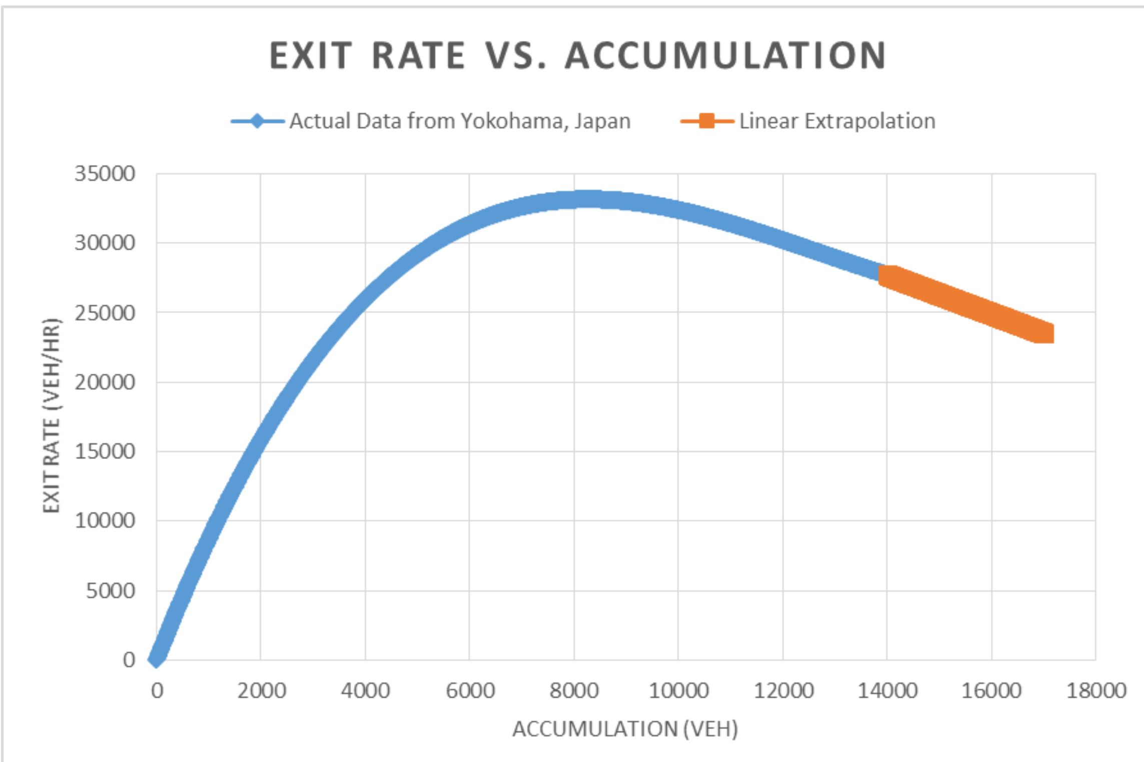


Figure 6. Graph of Network Exit Function (NEF)

The fundamental relationship (see Equation 3) in which this study relies on is that the accumulation in any system is equal to the difference between the number of trips started and number of trips completed. Using this, it is possible to describe the number in the downtown at time *t* [D(t)] as a function of the cumulative number that have entered [A(t)] and the cumulative number that have completed their trips [L(t)].

Equation 3. Accumulation for Any System

$$D(t) = A(t) - L(t)$$

To utilize this basic relationship for accumulation, it is necessary to translate this information into terms that are being used in this study. Equation 4 represents this translation to terms defined in this study.

Equation 4. Accumulation for Network Structure at Initial Time

$$D(t) = A_i(t) + M(t) - L(t) + D(0)$$

Equation 4 strictly represents the accumulation only at the start of a time interval. It is important to note that this equation represents the accumulation at a distinct point in time rather than for a time interval. In this study, it is assumed that at the initial time, the network has both internal and external trip generation, but does not have an initial accumulation since the system is assumed to have no trip generation prior to the interval of time under investigation. Although Equation 4 offers information about a distinct point in time, it is necessary to understand how the accumulation changes over an interval of time. Therefore, Equation 4 needs to be modified to fit an interval in time as illustrated in Equation 5.

Equation 5. Accumulation for Network Structure for Time Interval

$$D(t + \Delta t) = D(t) + \left[[a_i(t) + \mu(t) - l(t)] * (\Delta t)\right]$$

The accumulation over an interval of time is largely dependent on Equation 1, which describes the direct relationship between the exit rate and accumulation. Therefore, Equation 6 incorporates this relationship by introducing Equation 1 into the function describing the accumulation over an interval of time (Equation 5).

Equation 6. Accumulation for Network Structure with Incorporated NEF Relationship

$$D(t + \Delta t) = D(t) + \left[\left[a_i(t) + \mu(t) - f\big(D(t)\big)\right] * (\Delta t)\right]$$

After the first interval of time [Δt], there were travelers that had entered the system, due to the non-zero prescribed arrival rates, but did not complete their trips. With the incomplete trips, an accumulation within the downtown area became non-zero after the first interval of time. This non-zero accumulation directly correlated to a non-zero exit rate

Six different case studies were simulated, each represented by different network arrival rates. Six different arrival rates were chosen to represent different demand patterns that might be expected for a congested city-center. They were also chosen for simplicity in modeling, and because most major cities experience very high demands from outside of the downtown area. Three constant arrival rates and three piecewise linear arrival rates were simulated. The length of the peak demand period was also varied. All arrival rates were generated so as to achieve approximately the same maximum accumulation when no metering strategy was applied. Therefore, the greatest arrival rates had the shortest time intervals and smaller arrival rates had longer time intervals. The former might represent a short but intense peak period while the latter a less intense but sustained peak. The internal network arrival rate was set to approximately one-third of the external network arrival rate and has an equal or longer duration than the external arrival rates duration. Refer to Appendix A for graphical representations of the six case study arrival rates.

Case 1:

Equation 7. External Arrival Rate for Case 1

$$a_e(t) = \begin{cases} 40{,}000; \; 0 \leq t \; \leq 0.75 \; hour \\ 0 * t; otherwise \end{cases}$$

Equation 8. Internal Arrival Rate for Case 1

$$a_i(t) = \begin{cases} 13{,}333; \; 0 \leq t \; \leq 1.00 \; hour \\ 0 * t; otherwise \end{cases}$$

Case 2:

Equation 9. External Arrival Rate for Case 2

$$a_e(t) = \begin{cases} 31{,}000;\ 0 \le t \ \le 1.50\ hours \\ 0 * t; otherwise \end{cases}$$

Equation 10. Internal Arrival Rate for Case 2

$$a_i(t) = \begin{cases} 10{,}333;\ 0 \le t \ \le 2.00\ hours \\ 0 * t; otherwise \end{cases}$$

Case 3:

Equation 11. External Arrival Rate for Case 3

$$a_e(t) = \begin{cases} 28{,}150;\ 0 \le t \ \le 2.25\ hours \\ 0 * t; otherwise \end{cases}$$

Equation 12. Internal Arrival Rate for Case 3

$$a_i(t) = \begin{cases} 9{,}383;\ 0 \le t \ \le 3.00\ hours \\ 0 * t; otherwise \end{cases}$$

Case 4:

Equation 13. External Arrival Rate for Case 4

$$a_e(t) = \begin{cases} 43{,}500 * t;\ 0 \le t \ \le 1.00\ hour \\ 87{,}000 - (43{,}500 * t); 1.00\ hour < t \le 2.00\ hours \end{cases}$$

Equation 14. Internal Arrival Rate for Case 4

$$a_i(t) = \begin{cases} 14{,}500 * t;\ 0 \le t \ \le 1.00\ hour \\ 29{,}000 - (14{,}500 * t); 1.00\ hour < t \le 2.00\ hours \end{cases}$$

Case 5:

Equation 15. External Arrival Rate for Case 5

$$a_e(t) = \begin{cases} 25{,}500 * t;\ 0 \le t \ \le 1.50\ hours \\ 76{,}500 - (25{,}500 * t); 1.50\ hours < t \le 3.00\ hours \end{cases}$$

Equation 16. Internal Arrival Rate for Case 5

$$a_i(t) = \begin{cases} 8{,}500 * t; \ 0 \leq t \ \leq 1.50 \ hours \\ 25{,}500 - (8{,}500 * t); 1.50 \ hours < t \leq 3.00 \ hours \end{cases}$$

Case 6:

Equation 17. External Arrival Rate for Case 6

$$a_e(t) = \begin{cases} 17{,}700 * t; \ 0 \leq t \ \leq 2.00 \ hours \\ 70{,}800 - (17{,}700 * t); 2.00 \ hours < t \leq 4.00 \ hours \end{cases}$$

Equation 18. Internal Arrival Rate for Case 6

$$a_i(t) = \begin{cases} 5{,}900 * t; \ 0 \leq t \ \leq 2.00 \ hours \\ 23{,}600 - (5{,}900 * t); 2.00 \ hours < t \leq 4.00 \ hours \end{cases}$$

The relationships described previously to qunatify accumulation represent a situation in which no perimeter control techniques were being used. Because of this, the traffic network had external trips arriving to the system in an uncontrolled fashion such that $\mu(t) = a_e(t)$ in reference to the network structure outlined in Figure 5. Because there was no perimeter control technique between the suburban area and the downtown area, one could expect the accumulation in the downtown area to be greater than a system in which perimeter metering techniques are implemented. The arrival rates, $a_e(t)$ *and* $a_i(t)$, were both at full-capacity entering the downtown system for their designated time intervals without any controlled input into the system whatsoever. As proposed by Daganzo (2007), one can recognize that, without any control techniques, once the accumulation exceeded the optimal accumulation [R], there would be a "positive feedback" cycle in which the accumulation continues to build on itself. As accumulation continues to build and the vehicles continue to flow into the system, the system works itself towards a state of "gridlock" because of higher accumulations and lower exit rates. This continues until the arrival rates decreases, exit rate increases, and accumulation eventually begins to dissipate.

The network arrival rates prescribed for Case 1 were chosen as an example to describe the following computations. All calculations were performed using Microsoft Excel. As depicted in Table 2, a consistent format was used for all six cases where the network arrival rates, exit rates, and assumptions were included on each simulation run due to the dynamic dependencies described previously.

Table 2. Microsoft Excel Table of Simulation Parameters

			Given			
Time Interval	0.0 hr	to	7.750 hr	Step by	0.00028 hr	
External Arrival	40000		from	0.0 hr	to	0.75 hr
Function [$a_e(t)$]	0		from	0.75 hr	to	infinity
Internal Arrival	13333		from	0.0 hr	to	1.00 hr
Function [$a_i(t)$]	0		from	1.00 hr	to	infinity
	2.28E-08	* $[D(t)]^3$	from	0 veh.	to	14000 veh.
	-0.000862	* $[D(t)]^2$				
Exit Rate [$l(t)$]	9.58	* [D(t)]				
	27731		from	14000 veh.	to	infinity
	1.4	* [D(t)]				
	D(0) = 0		Control Accum.	**8600 veh.**		
Assumptions:	l(0) = 0		Optimal Accum.	8271 veh.		
	Slope of l(0) = 0		f(Opt. Accum.)	33168 veh/hr		

The following list of steps represent the process that was followed to quantify the total travel time of all travelers within the traffic network. This travel time is crucial in the analysis of the equity and efficiency of a traffic network because it sets a baseline to which metering techniques should improve upon.

1. A time interval was chosen for the simulation. The time interval was set to be 0 to 7.75 hours, stepping by one second between each calculation. (i.e. Δt = 1 second).
2. The external trip generation rate to the system [$a_e(t)$] was then applied for the specified duration. For Case 1, this arrival rate was 40,000 veh/hr until the time for the simulation was equal to 0.75 hours. Once 0.75 hours was surpassed, the arrival rate was set equal to zero based on the prescribed conditions. Since no metering technique was being used, $\mu(t) = a_e(t)$.
3. The number of arrivals during the constant measurement period of one second was then calculated by multiplying the arrival rate at a certain instance in the simulation by the time

between measurements. A cumulative count of the arrivals [$A_e(t)$] during the time interval was included in the analysis.

4. Steps two and three were repeated for the trip generation arrival rate within the downtown system, $a_i(t)$ and $A_i(t)$.
5. The accumulation during the first measurement period was calculated from Equation 4. Based on assumptions outlined previously, at time t = 0 hours, the accumulation [D(t)] and exit rate were both equal to zero. Since all other parameters were known, it was possible to find the accumulation during the first measurement period. The accumulation was calculated from Equation 6 for all times after t = 0 hours.
6. The accumulation calculated in step 5 was compared to the function intervals for the exit rate. If the accumulation was less than 14,000 vehicles, the current accumulation value was inserted into the exponential exit function (see Equation 2). Otherwise, the accumulation was plugged into the linear exit rate (see Equation 2). This provided an exit rate at a specific instance in time during the simulation.
7. The next step was to multiply the exit rate found in step 6 by the measurement period of one second. A cumulative count of the number of trips completed [L(t)] was important once the simulation concluded.
8. Steps 5 through 7 were repeated until the accumulation during the measurement period was equal to zero.
9. The total travel time [TTT] at each instance of time was measured (every one second) based on the following formula:

Equation 19. Total Travel Time for Non-Metering Case

$$TTT_{Non-Metering} = \Big(\big(A_e(t) + A_i(t)\big) - L(t)\Big) * \Delta t$$

10. All calculated travel times were aggregated to find the total travel time in the network.

Metering Scenarios

In this study, there are two types of trips: external trips that are arriving to the network and uncontrollable, internal trips generated within the downtown system. As the number of trips using the network builds over time, an accumulation of unfinished trips will develop if some of the trips within the downtown system are not able to be completed. This cumulative cycle continues until the accumulation reaches an optimal value [R]; this value is based on the rate at which trips are being completed. Until this optimal value is met, the system is able to operate in a stable manner. Once this optimal value is met and surpassed, the system exhibits unstable behavior. Unstable behavior includes an overload of travelers in the system, which makes the system more congested and reduces the rate at which trips can be completed. This increased level of congestion causes the system to act in a manner that is less efficient than its stable counterpart and can eventually lead to a state of gridlock. Therefore, it is best to implement a perimeter control strategy at times when the optimal accumulation is exceeded. This control strategy must be instituted because the system would otherwise move towards a state of gridlock. The control strategy that was utilized in this network structure was to implement a perimeter metering strategy for the travelers entering the downtown system from the suburb area. At times in which there was not an accumulation beyond the optimal value, the trips entering from the suburb were not metered because the system was operating in a stable state. In other words, the accumulation in the downtown area is less than the control accumulation, $\mu(t) = a_e(t)$. If the accumulation in the downtown network is greater than the optimal accumulation, metering takes place, such that $\mu(t) \neq a_e(t)$. In this study, two different metering strategies were developed to understand how the strategies could possibly improve the efficiency of an entire traffic network by inevitably generating a geographical inequity. Although operating at the optimal accumulation coincides with the most efficient system, additional simulations were run to understand how the efficiency and equity change when the metering occurs at accumulations other than the optimal value. This accumulation value, called the control accumulation [C], is the value at which metering is triggered during the simulations.

Static Metering Technique

This technique incorporates the most common metering approach proposed in the literature. Specifically, this technique features a cyclical pattern to minimize the number of vehicles delayed. One can think of this metering technique in terms of the methodology of using a reservation system at a restaurant. Rather than having a very inconsistent flow of walk-in customers, a lot of restaurants are now encouraging their patrons to use reservation services. They are attempting to do this so that they are able to maintain a nearly consistent flow of patrons so that their employees maintain an adequate level of customers and are not overwhelmed with too many patrons at one time. Maintaining a nearly steady demand limits variability in terms of the customers waiting time and the time it takes for the moderately busy employee to serve their table. With this technique, maintaining a nearly constant accumulation limits the variability and duration to which travelers in the network experience. This was done by maintaining the rate at which the external trips could enter the downtown system at its indicated rate [$a_e(t)$] until the specified control accumulation [C] was exceeded. Once this threshold was met and exceeded, the external trips were stopped at the perimeter of the downtown system and held in the suburb area until the accumulation in the downtown system [D(t)] was less than the control accumulation. Once the accumulation in the downtown system decreased to less than the control accumulation, the trips being delayed in the suburb were allowed to enter the downtown system at a modified rate. This modified rate represents the difference between the optimal exit rate and the prescribed internal arrival rate at a distinct interval of time [$l(R) - a_i(t)$]. This cyclical process continued until all of the trips were able to be completed. Equation 20 illustrates this metering approach in terms of the variables used in this study.

Equation 20. Arrival Rate from Suburb to Downtown - Static Metering

$$\mu(t) = \begin{cases} a_e(t)\ when\ D(t) \le C\ and\ S(t) = 0 \\ l(R) - a_i(t)\ when\ D(t) \le C\ and\ S(t) > 0 \\ 0;\ otherwise \end{cases}$$

Pump and Hold Metering Technique

This traffic control technique uses a metering approach to regulate the external trips attempting to enter the downtown system. This operates by maintaining a prescribed trip generation rate until the control accumulation [C] value is met. Once this control accumulation value is met, the system inhibits the flow into the downtown area until the accumulation in the downtown area [D(t)] is equal to the optimal accumulation [R] of 8,271 vehicles. This strategy only applies for tests of control accumulation greater than 8,271 vehicles. After this threshold was met, the system resumes in a similar manner to the static metering technique, where the accumulation needs to remain at the optimal accumulation of 8,271 vehicles. One can think of this metering technique as a similar method that is used at entrance gates for large athletic events. When patrons arrive early to an event, such as a Penn State football game, there are typically a lot of attendants letting patrons into the stadium at first to push as many people through the gate as quickly as possible once the gates open. After they handle the first surge of patrons that arrived to the gate, they cut back on the number of attendants, say from 20 for the initial surge, to 10 during times after the initial surge is met to keep a constant flow of patrons flowing through the gates until the event begins. The reason that this decrease in attendants is effective is because it manages the inflow of patrons so that they have to wait in shorter lines rather than no line at all, so that all attendants are busy at all times. Therefore, this strategy attempts to meet an initial surge and then maintains a steady accumulation until the demand decreases. Equation 21 illustrates this metering approach in terms of the variables used in this study.

Equation 21. Arrival Rate for Travelers from Suburb – Pump and Hold Metering

$$\mu(t) = \begin{cases} a_e(t) \text{ when } D(t) \leq C \text{ and } S(t) = 0 \\ l(R) - a_i(t) \text{ when } D(t) \leq R \text{ and } S(t) > 0 \\ 0; \text{ otherwise} \end{cases}$$

In addition to following steps 1 thru 10 for computing the total travel times for the non-metering case, one must also follow these additional steps to calculate the parameters for the metering techniques.

This list of steps was applied for each control accumulation simulated, which included tests from 7,000 vehicles (or 8,600 vehicles for the pump and hold metering technique) to 17,000 vehicles, stepping by 400 vehicles for each test.

11. Conditional if-statements, as described by Equations 20 and 21, were generated in Microsoft Excel.
12. Steps 5 thru 8 were repeated for the metering techniques.
13. The total travel time [TTT] was calculated at each instance of time measured (every one second) based on the following formulas:

Equation 22. Total Travel Time in Downtown System for Metering Techniques

$$TTT_{Metering-Downtown} = \Big(\big(M(t) + A_i(t)\big) - L(t)\Big) * \ \Delta t$$

Equation 23. Total Travel Time in Suburb Area for Metering Techniques

$$TTT_{Metering-Suburb} = \big(A_e(t) - M(t)\big) * \ \Delta t$$

Equation 24. Total Travel Time in System for Metering Techniques

$$TTT_{Metering-System} = TTT_{Metering-Downtown} + TTT_{Metering-Suburb}$$

14. All calculated travel times were aggregated to have three independent values: the total travel time in the network, downtown, and in the suburb.

Chapter 4

Results & Discussion

Downtown System Accumulation

At the conclusion of a simulation, a graph that compared the downtown system accumulation versus time was generated for the two metering strategies and non-metering case (see Figure 7). This graph is useful to ensure that, from a broader scale, the simulation ran correctly and to compare overall operations when metering is applied and when it is not. Figure 7 depicts Case 1 with a control accumulation of 13,000 vehicles.

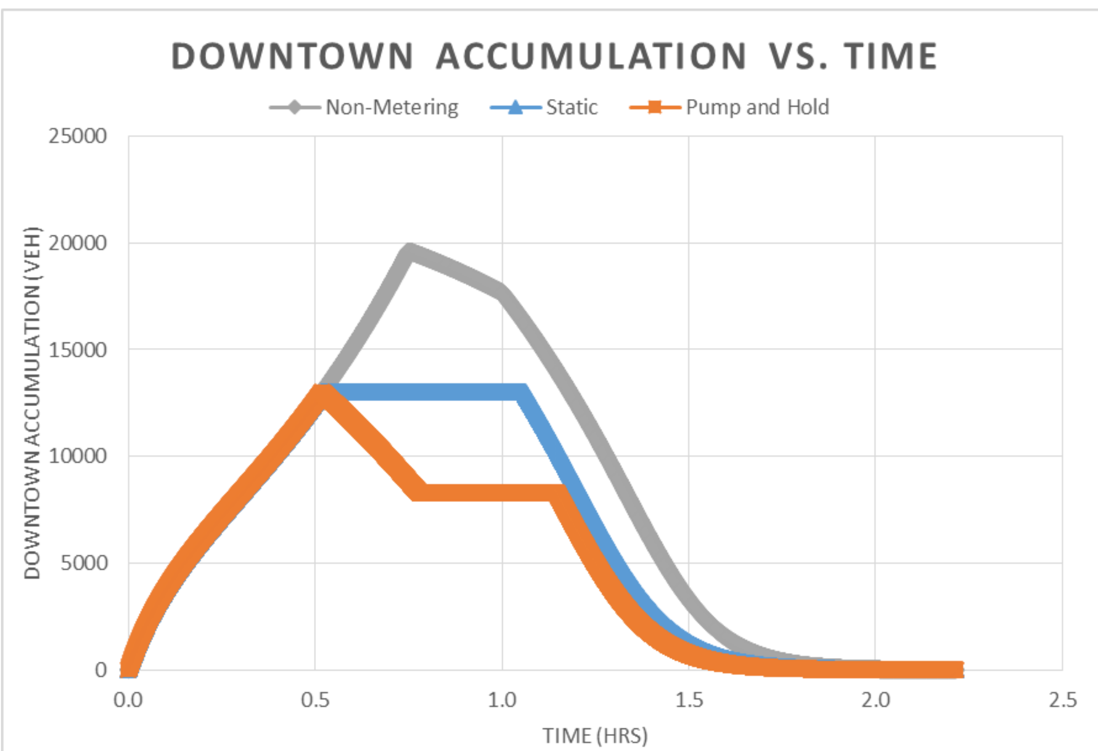


Figure 7. Comparison of Downtown Accumulation Versus Time

In analyzing the effectiveness of the two different metering techniques, this graph illustrates how maintaining an accumulation around the optimal accumulation found from the network exit function [D(t) = 8,271 veh] minimizes the amount of time that metering is required. Furthermore, this graph illustrates the general curvature expected for the metering techniques. The non-metering case reaches a maximum once all of the vehicles have had a chance to arrive from the external arrival rate [$a_e(t)$]. Once this maximum point is reached, the flatter negative curvature (between approximately 0.75 hour and 1 hour) represents the duration when trips are being generated internally only. Once this trip generation arrival rate concludes, the downtown accumulation [D(t)] begins to decrease more rapidly as the exit rate begins to increase until the accumulation is gradually depleted. The static metering strategy, despite having minor variations due to the cyclical relationship of maintaining an accumulation around the control accumulation [C], should generally be represented by a horizontal line until metering is no longer necessary. The pump and hold metering strategy also incorporates a similar metering approach where the downtown accumulation remains around the optimal accumulation following meeting its initial surge.

Queuing Diagrams

In order to interpret the data generated from the simulation, queuing diagrams were created to graphically represent the cumulative number of vehicles that arrived and departed at a macroscopic scale. A queuing diagram offers information about key components that are needed to ultimately describe efficiency and equity, which include accumulation, total travel time, and total delay.

Figure 8 represents a queuing diagram of the downtown area for Case 1 at a control accumulation of 13,000 vehicles; before aggregating specific data, it is very important to analyze this diagram. Important behavior of the traffic control techniques can be observed on this diagram in addition to being able to qualitatively understand which traffic control technique is most effective. Each traffic control technique is represented by two continuous curves (of the same color on this particular diagram). The upper curve (left-most curve) represents the cumulative number of trips generated into the downtown area, both internally and externally [$A_e(t)$ and $A_i(t)$]. The lower curve (right-most curve) represents the cumulative number of trips completed [$L(t)$]. The alignment of these curves is intuitive because there cannot be more trips completed than the amount that have been started. The two curves should converge at a point once all of the vehicles that began trips have completed their trips. It is a good check of accuracy to make sure that all traffic control techniques converge at the same level of arrivals and departures. The vertical distance between the arrival and departure curves represents the accumulation at a particular time in the downtown area. The horizontal distance between the two curves represents the total travel time in the downtown area at a particular time. Finally, the total area between the curves represents the total delay in the downtown area. The simulation showed similar trends for the six case studies. For simplicity, only the constant Case 1 function and the piecewise linear Case 4 function is described in more detail, using a control accumulation of 13,000 vehicles.

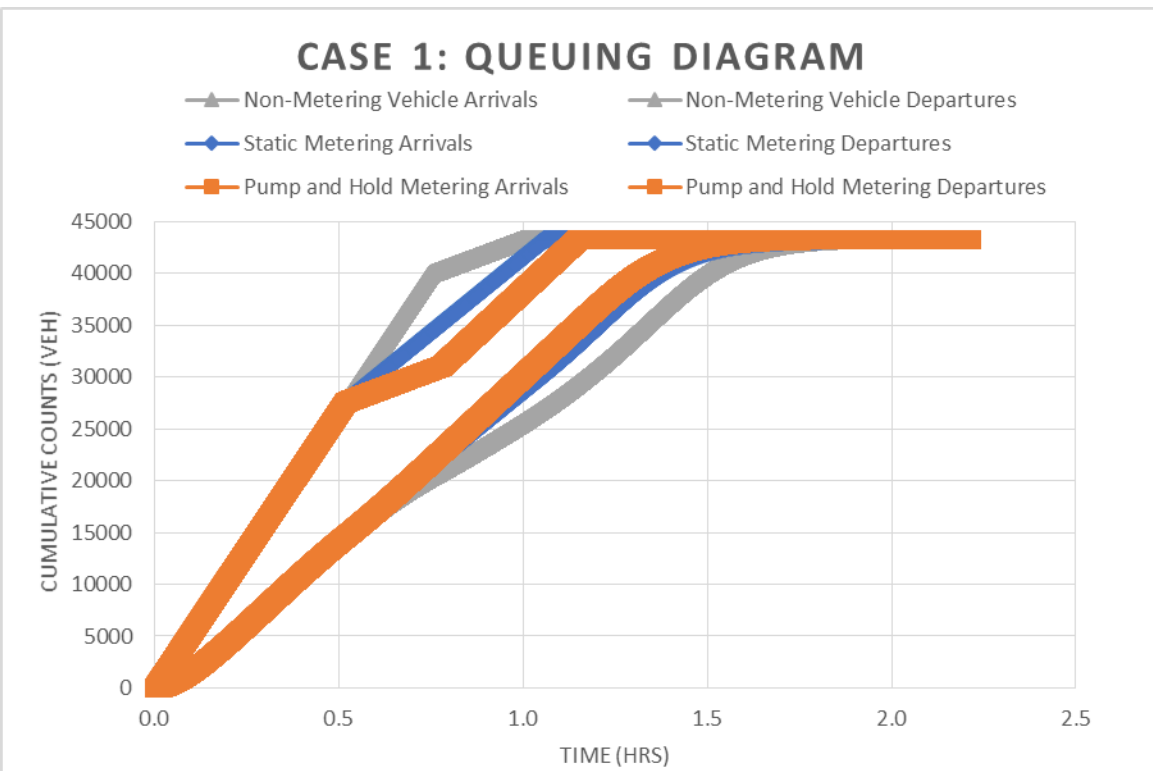


Figure 8. Queuing Diagram of Downtown Area for Case 1 at Control Accumulation of 13,000 Vehicles

The queuing diagram depicted in Figure 8 yields trends that seemed to be prevalent throughout Cases 1, 2, and 3 and throughout many of the simulations at different control accumulations. The greater the horizontal and vertical distance between the arrival and departure curves on the queuing diagram, the greater the travel time and accumulation. It is important to note that the non-metering case was, by far, the least effective. One could expect that this is the case because traffic control techniques are used in a network in the first place to decrease the total travel time, accumulation, and delay for travelers.

The non-metering arrival curve increases linearly until the external arrival rate [$A_e(t)$] concludes. Once this occurs, the flatter slope between 0.75 hour and 1 hour represents only the internal arrival rate within the downtown area [$A_i(t)$], which was set to have a longer time interval than the non-zero arrival rate to the system. At 1 hour, both arrival rates are zero, which means that there will not be any more trips being generated. The cumulative exit curve [L(t)] for the non-metering case represents a system moving towards a state of gridlock. As the slope begins to decrease near 0.75 hour, the accumulation and total travel time are increasing. This decrease in slope occurs because of the build-up of accumulation in the system, which is where the metering techniques differ from this non-metering case. The increase in slope seen at 1.25 hours represents the decrease in accumulation once both of the arrival rates become zero.

Analyzing the metering techniques on the queuing diagram from a macroscopic level, it is noticeable how the different strategies appear to have fundamental differences in controlling the traffic flow, but all represent viable traffic control techniques. The divergence in the metering technique arrival curves just after 0.50 hour is the time at which the control accumulation [C] is met. Prior to meeting this control accumulation, the travelers entering the system were not undergoing any metering whatsoever.

The static metering technique controlled the external arrivals to the traffic network, $A_e(t)$, so that the accumulation in the downtown area remained near the control accumulation. As indicated in Figure 8, the fact that the arrival and departure curves lie within the bounds of the non-metering curvatures indicates that the accumulation, total travel time, and total delay is less than the non-metering case. With that being said, one advantage of this system is the nearly uniform travel times once metering begins. Once metering begins, the nearly constant difference in horizontal distance between the arrival and departure curves indicates that there is a nearly uniform travel time for all vehicles traveling through the system, despite what time they arrive and depart from the traffic network. Another advantage of this technique is the duration of time that this technique took to allow all vehicles entering the system to exit the system. Finally, one other advantage of this system is that the accumulation never increases beyond the control accumulation which prohibits the possibility of the network becoming overcrowded.

For this particular control accumulation, the pump and hold metering technique offered the most efficient system in terms of the total travel time as the arrival and departure curves remain with the bounds of the static metering technique curves. With that being said, the flatter positive slope between approximately 0.50 hours and 0.75 hours is a time in which only internal trips are being generated, which decreases the total travel time for the downtown travelers, but at a cost of metering individuals in the suburb. The decrease in downtown accumulation and travel time during this 0.25 hour time range causes an inequity to the travelers being metered in the suburb. This is because they experience a much more significant travel time than their counterparts that made it in to the downtown area prior to metering taking place. Whereas static metering aimed to keep a nearly constant delay in the suburb by having cyclical periods of metering, the pump and hold strategy attempts to pass as many travelers through the system and then delays a subset of the travelers traveling from the suburb for a longer duration of time. This variation of total travel time, delay, and accumulation with time could serve as an advantage to some and a disadvantage to others depending on when and where (downtown or suburb) the traveler began their trip. A disadvantage to this technique is the variation and inconsistency in terms of treating the travelers within the network; some are at an advantage based on when or where they arrive and others encounter significant delays because they arrived when or where metering is occurring.

Figure 9 illustrates similar trends for Case 4 (operating with a control accumulation of 13,000 vehicles) as those that were seen with Case 1. The most significant difference is the curved rather than linear nature of the arrival and departure curves based on the piecewise linear arrival functions. One notable feature of this queuing diagram is the concavity prior to metering occurring. Despite having a different arrival rate than the one illustrated in Figure 8, the gradually changing arrival rate did not change the trends, discussed previously, of the non-metering case and two different metering strategies.

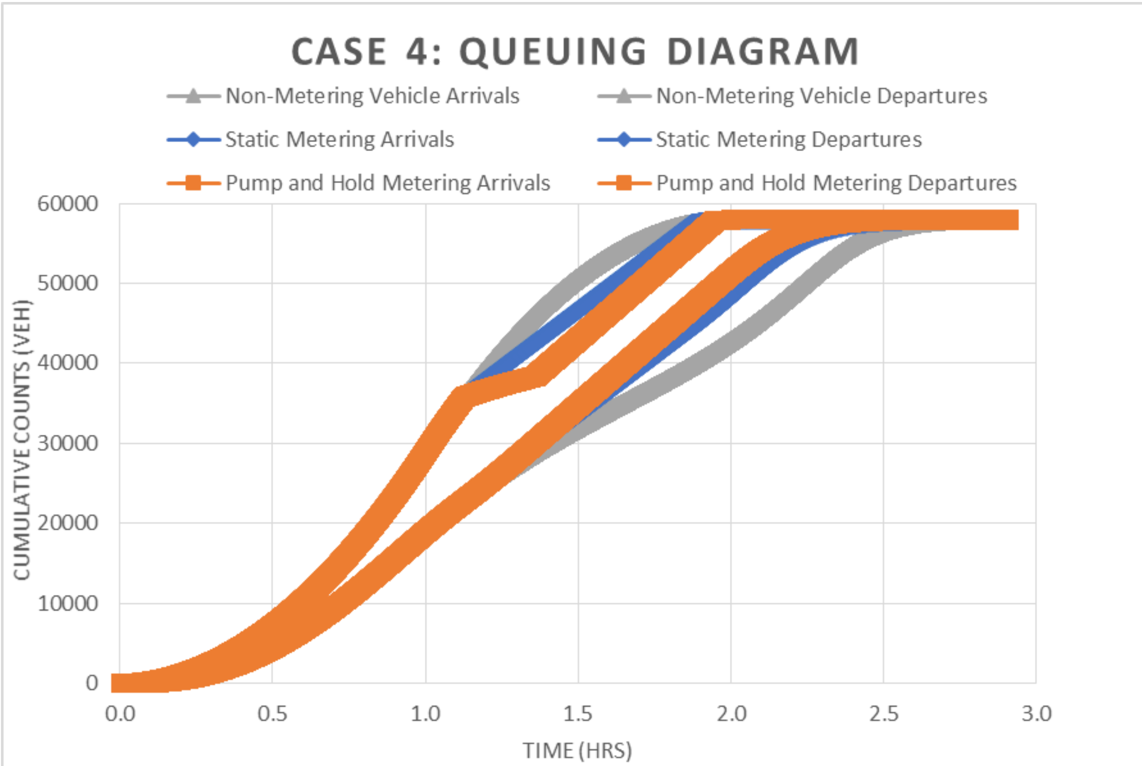


Figure 9. Queuing Diagram of Downtown Area for Case 4 at Control Accumulation of 13,000 Vehicles

Total Travel Time Comparison

During the series of simulations with control accumulations ranging from 7,000 to 17,000 vehicles, an emerging trend formed with regards to the travel time for its users. This trend seemed to indicate that, as expected, the minimum value of total travel time within the entire network occurred when the control accumulation [C] was equal to the optimal accumulation [R], which in this case, was 8,271 vehicles. Therefore, this optimal accumulation served as the minimum point in the comparison of the total travel time within the traffic network and the control accumulation. One could expect that this would be the case because if the network maintains an accumulation near the optimal value, the exit rate [l(t)] also operates at its maximum value. This is because the optimal accumulation represents the maximum exit rate in the NEF. Figures 10 and 11 illustrate identical performance in terms of the metering approaches for Cases 1 and 4, respectively.

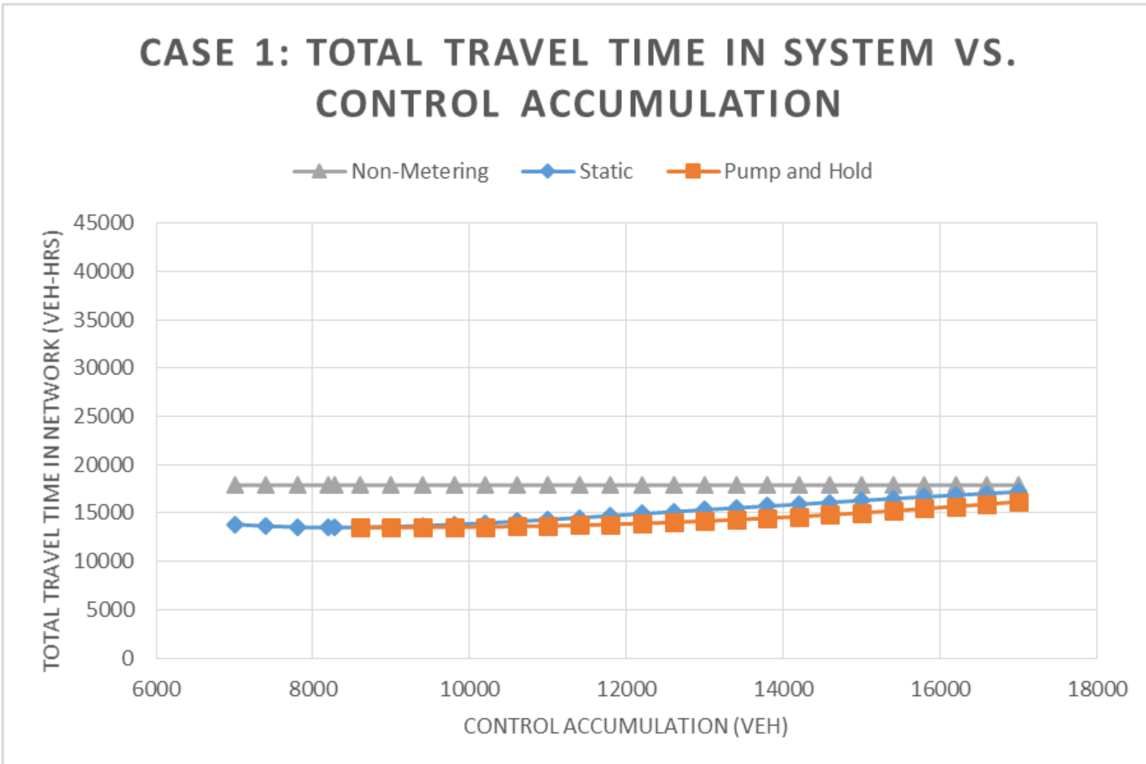


Figure 10. Comparison of Total Travel Time in Network Versus Different Control Accumulations for Case 1

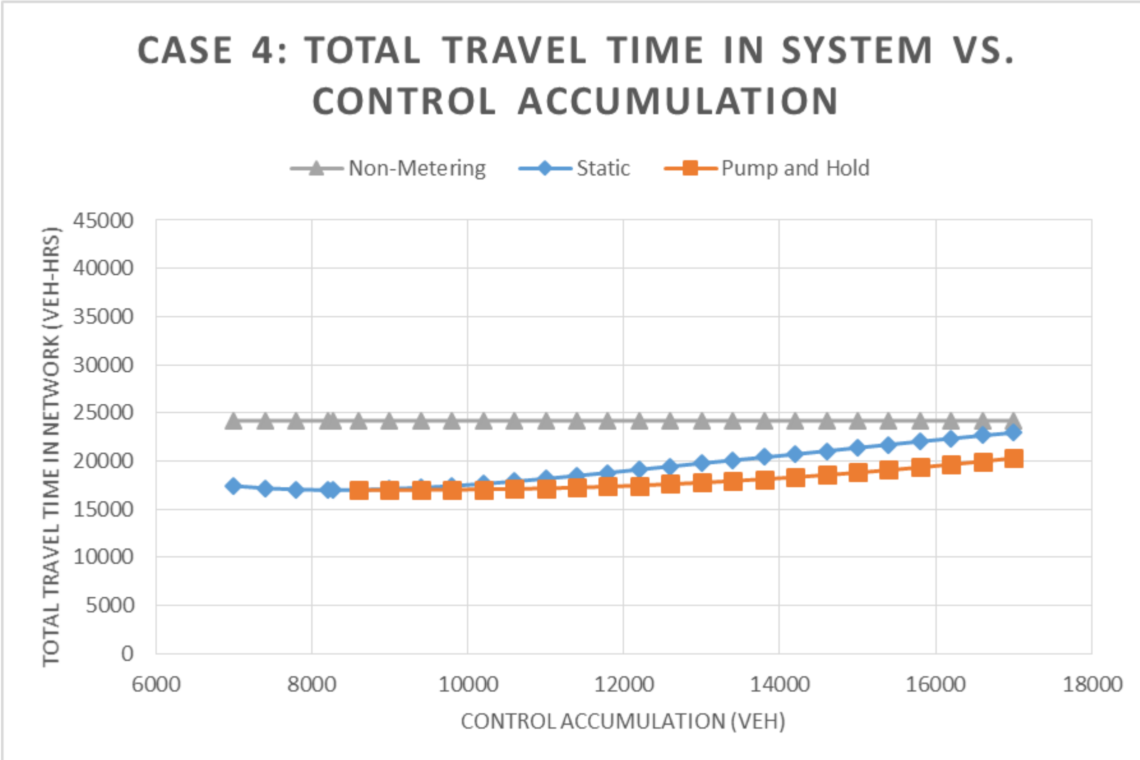


Figure 11. Comparison of Total Travel Time in Network Versus Different Control Accumulations for Case 4

As illustrated in Figures 10 and 11, a similar trend exists where both metering techniques approach the total travel time in the non-metering case as the control accumulation increases. In particular, one can also notice that the static metering approaches the non-metering case more rapidly than the pump and hold metering technique. This can be explained by the limited duration of the metering, which also limits the amount of vehicles being metered. If metering does not occur until 17,000 vehicles enter the network, then static metering is not going to occur until much later into the time interval than having a control accumulation closer to 8,271 vehicles. Furthermore, when the downtown accumulation is maintained at a high control accumulation, such as 17,000 vehicles, the rate at which travelers are able to exit is significantly less than lower control accumulations based on the decreasing slope on the NEF.

It was also expected that the pump and hold metering technique would perform more effectively in terms of total travel time within the system than the static metering technique as the control accumulation increased. This was expected because the pump and hold metering technique acts similar to the static metering technique operating at the optimal accumulation once the initial surge is met. As discussed earlier, the closer to the optimal accumulation, the greater the rate at which travelers can exit from the network. The static metering technique maintains a downtown accumulation near the control accumulation, which is not necessarily beneficial in terms of the rate at which vehicles are able to exit the network.

Since the six cases had a maximum accumulation near 19,500 vehicles, any control accumulation greater than approximately 19,500 would effectively be useless, as the system would never experience an accumulation greater than the control accumulation. See Appendix B for a comparison between the total travel time in the network and the control accumulation for all six cases.

Efficiency and Equity Analysis

In order to integrate a metering technique into a traffic system properly, it is vital to understand how it may affect those using the traffic system. Therefore, this trade-off between an efficient system and equity for users of the system is an important trade-off to consider. The total travel time in the network was chosen to represent the efficiency of the system. This was chosen because it represents how quickly vehicles were able to pass through the entire suburb-downtown traffic network. Intuitively, the shorter the amount of time spent in the system, the more efficient the system proves to be. Equity was represented by the total travel time in the suburb. This parameter was chosen to represent equity because it is a measurable parameter representing the total time a vehicle had to wait to enter the downtown area. Once again, the shorter the amount of time spent in the suburb, the more equitable the system. As a method to normalize the data, a best case was chosen to provide the data in a more comparative manner than raw data. This best case was chosen to be the total travel times for the static metering technique operating at the optimal accumulation [R]. Table 3 lists the total travel times used as the basis for normalizing the rest of the data. Figure 12 is a comparison, for Case 1, between the inequity and inefficiency of the network. These axes indicate that smaller values closer to the origin (0,0) are desired. This means that higher percentages would have higher travel times than the best case, which is the basis for desiring lower values of inequity and inefficiency.

Table 3. Total Travel Time for Normalizing Data

	Total Travel Time in System [veh-hrs]	*Total Travel Time in Suburb [veh-hrs]*	*Total Travel Time in Downtown [veh-hrs]*
Case 1	13514	3946	9568
Case 2	19576	4595	14981
Case 3	24930	4676	20254
Case 4	16997	4638	12360
Case 5	21157	5084	16073
Case 6	24516	5107	19409

As depicted in Figure 12, a relationship between equity and efficiency does exist. This trade-off exists because there is not one solution to make a perfect system; in other words, it is not possible to make a system more efficient and more equitable simultaneously. As discussed previously, a subset of the individuals traveling from the suburb inherently (those metered) get disadvantaged because of where they live. This metering is necessary, though, to ensure that a system avoids congestion and potential gridlock. Therefore, the graph illustrated in Figure 12 shows this behavior of increasing the inequity or inefficiency in order to have a more equitable or efficient network. Having said this, there is a non-linear trade-off between the equity and efficiency associated with metering. This non-linear behavior illustrates that the control accumulation to which the network operates can have a significant effect on minimizing the decrease in equity or efficiency. In other words, for a relatively more equitable system, it may be possible to minimize the decrease in efficiency depending on the control accumulation the system operates at.

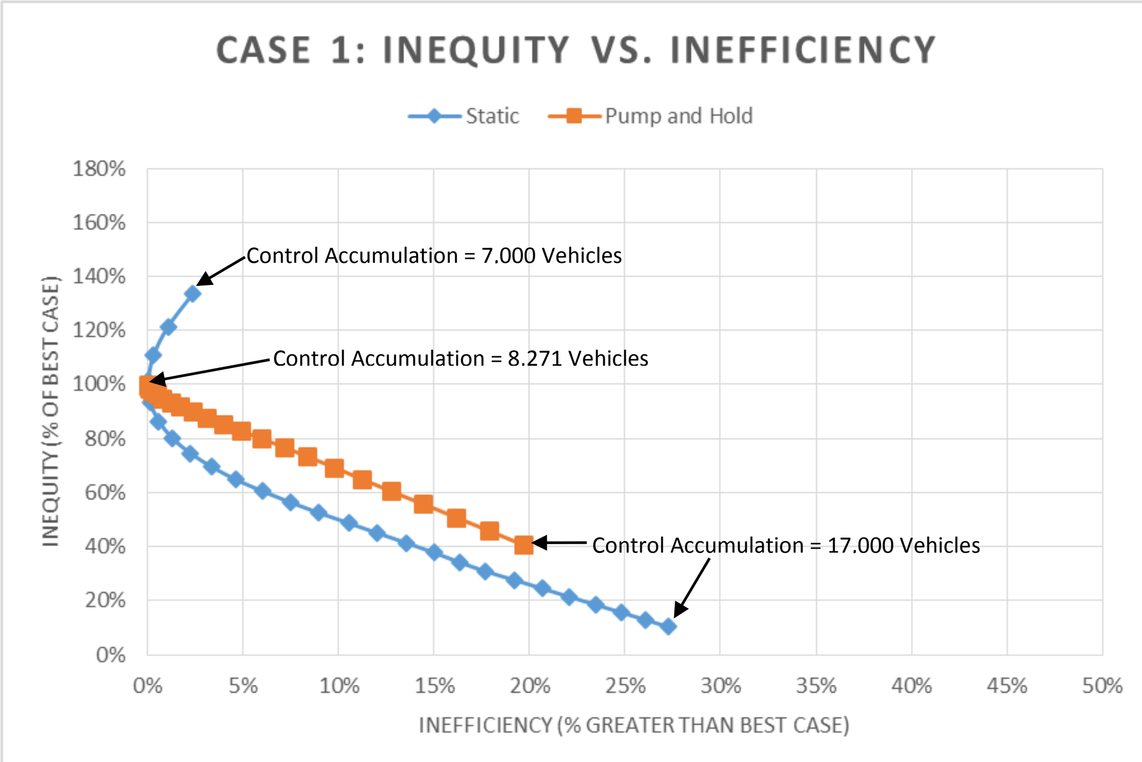


Figure 12. Comparison of the Inequity and Inefficiency for Case 1

To quantify the percentage changes in equity and efficiency, the elasticity was calculated at different control accumulations using the percent changes in total travel time with the suburb and network (see Equations 25 and 26).

Equation 25. Percent Change in Total Travel Times

$$Percent\ Change = \frac{New\ Value - Old\ Value}{|Old\ Value|} * 100$$

Equation 26. Elasticity Formula

$$Elasticity = \frac{\%\ Change\ of\ Inequity}{\%\ Change\ of\ Inefficiency}$$

In Case 1, it was found that the percent change between control accumulations near the optimal accumulation is nearly equal to zero, which is clear by the minimal separation between data points near the best case (0% inefficient, 100% inequitable) in Figure 12. The percent change for the total travel time in the network (represented by inefficiency) ranged between 0.03% to approximately 1.54% for the pump and hold metering technique. The percent change for the total travel time in the suburb (represented by inequity) ranged between -0.45% to approximately -11.53% for the pump and hold metering technique. Figure 13 shows a comparison of elasticity at different control accumulations for Case 1. It can be observed that most values on this graph are negative. This can be explained from the mostly decreasing slope depicted in Figure 12. As the inequity decreases, the inefficiency increases, causing a negative percent change for the inequity. Having a negative percent change directly correlates to a negative elasticity as explained by Equation 26. The positive elasticity at control accumulations lower than 8,600 vehicles represent the positive slope of the static metering curve in Figure 12, where the inequity and inefficiency are both increasing. Most negative values of elasticity are preferred since fairly mild changes in the inefficiency of a system can yield a higher percent change in inequity.

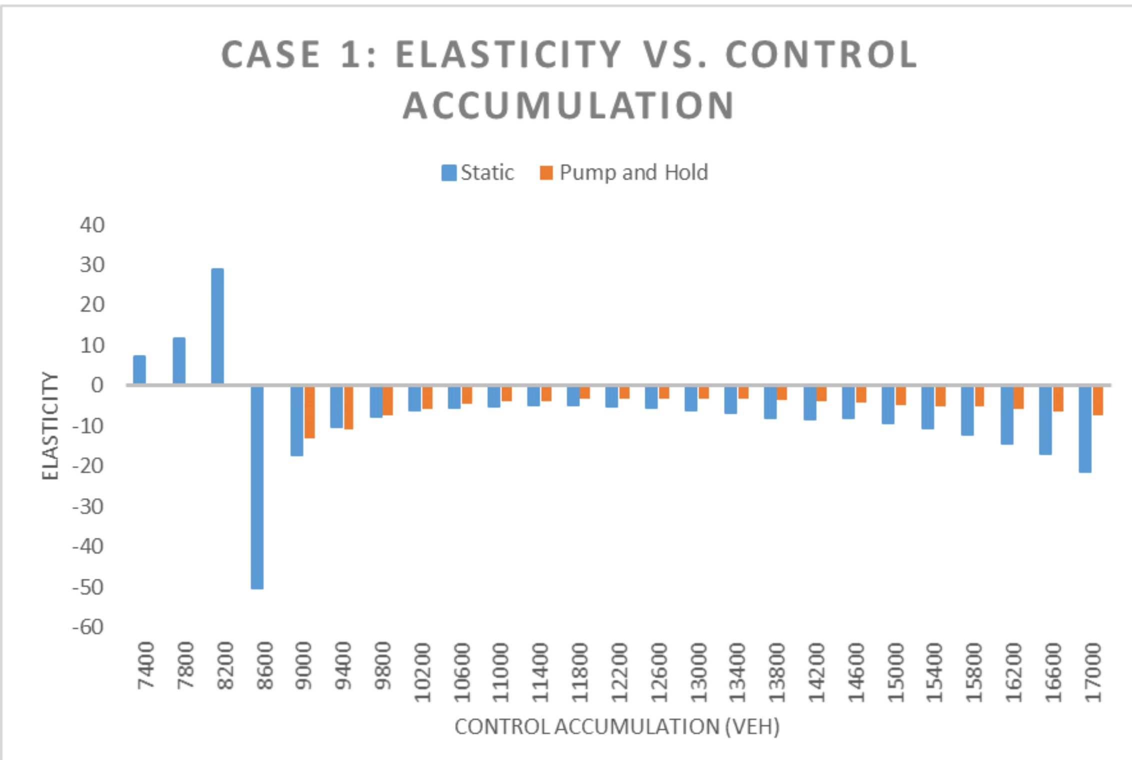


Figure 13. Comparison of the Elasticity at Different Control Accumulations for Case 1

Similar trends observed with the first three case studies also exist in the piecewise linear functions. Figure 14 represents the trade-off between inequity and efficiency for Case 4. As depicted in

Figure 14, the most notable difference is the flatter downward slope found with both metering strategies, and the percentage of inefficiency found at different control accumulations. This could be attributed to the variability of the arrival rates and increased time intervals to which vehicles arrive to the network. Figure 15 illustrates the elasticity associated with the control accumulations simulated for Case 4.

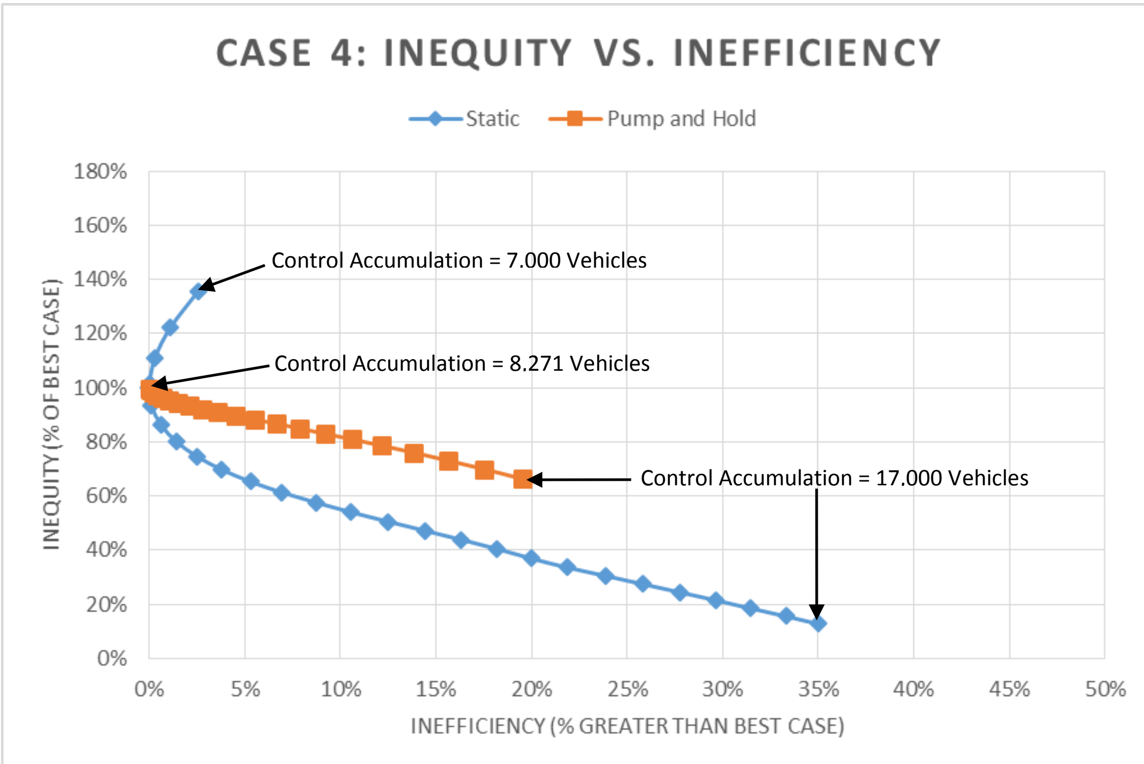


Figure 14. Comparison of the Inequity and Inefficiency for Case 4

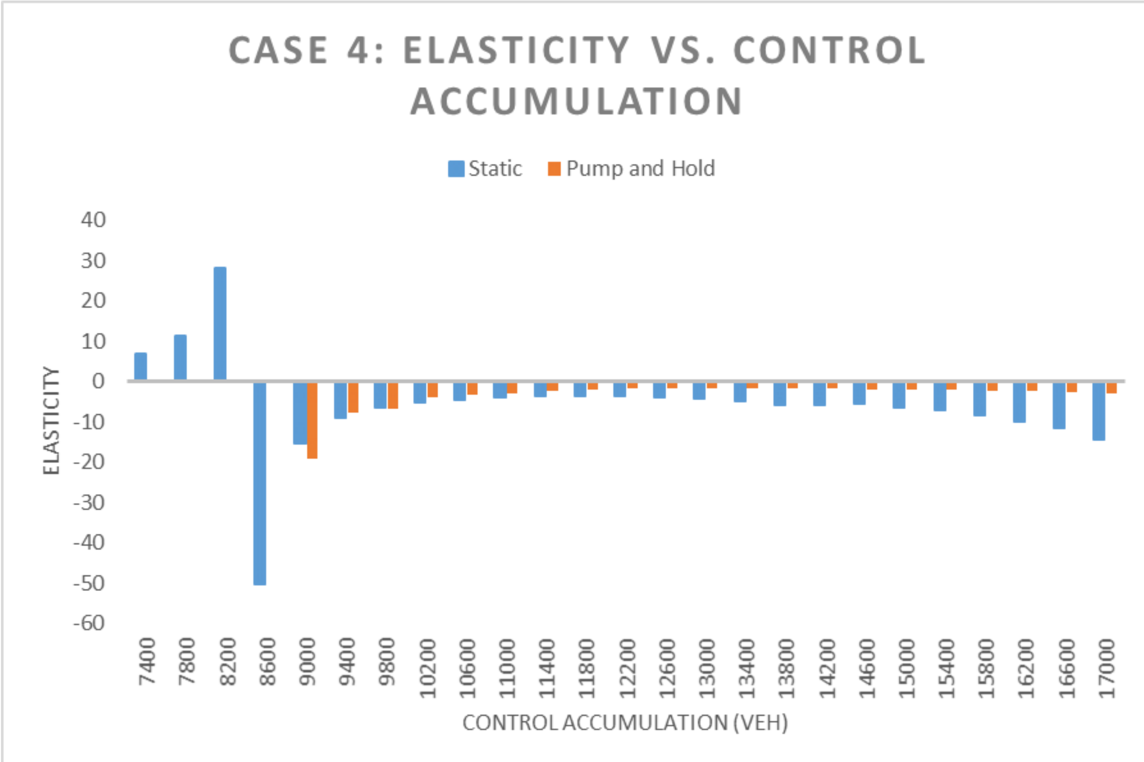


Figure 15. Comparison of the Elasticity at Different Control Accumulations for Case 4

Figures 12 through 15 illustrate how the metering strategy itself, and the way in which it is incorporated into a traffic network, can have an effect on traffic dynamics. Implementing a metering strategy offers a significant improvement in terms of the efficiency of the network as a whole, but this greater efficiency results in a decrease in equity for a subset of the systems users. With that being said, striking a balance near control accumulations that have largely negative values of elasticity could offer a possibility to reduce efficiency by the smallest amount to provide a substantial increase in the equity of a traffic network. It is also noticeable that the pump and hold strategy offers less opportunities to decrease the inequity as compared to the static metering strategy. This means that the pump and hold strategy inherently offers more geographic inequity than the static metering technique. The flatter slope of the pump and hold metering technique also indicates that it is possible to increase the efficiency in the network without much of a decrease in the equity. See Appendix C for graphs of the trade-off between inequity and inefficiency for all six case studies.

Chapter 5

Conclusion & Follow-Up

Summary of Research

This study discussed the trade-off between the equity and efficiency associated with two perimeter metering strategies implemented to decrease the congestion typically seen in urban traffic networks. The methodology to limit congestion controls the number of vehicles that are within the traffic network at one time (otherwise known as accumulation). A common technique used to control the accumulation is a metering strategy, which can be something as simple as incorporating traffic signals or gates at specific locations in a traffic network. In this particular study, one could think of placing traffic signals or gates at every perimeter entrance; as an example, it would be placing traffic signals or gates at the twenty access points to the Manhattan borough of New York City. Numerical simulations were created, using Microsoft Excel, to understand how long it took all travelers that entered an urban traffic network to complete their trips. The total amount of travel time was aggregated and then compared to two different perimeter metering strategies to understand how beneficial metering could be in improving how quickly all travelers finished their trips (otherwise known as efficiency). But, when improving the system, the perimeter metering strategies introduce an inequity by making the travelers entering the downtown from the suburb wait at a traffic signal or gate because the accumulation in the downtown region of the network was nearing a point of congestion. Therefore, this geographical inequity was calculated and normalized to understand how making a particular improvement to the efficiency affects the subset of the travelers who get metered in the suburb. In understanding the percentages associated with efficiency and equity, it is possible to choose a metering technique that best suits the needs of a particular urban network.

Few studies have been performed on this trade-off between equity and efficiency; the ones that have been done usually focus on pricing strategies rather than metering strategies as an option to control the inequities or inefficiencies that a subset of the population incur because of improvements to the overall network. Congestion is also growing rapidly and projections seem to indicate that this trend will continue. This growth in congestion is causing problems with delays to users, cost of gas, and a more significant amount of harmful chemicals being released from vehicle emissions. Any attempt to mitigate these issues can be costly, time consuming to execute, and can introduce a significant inequity if implemented incorrectly. An example of this could include building new infrastructure to meet current traffic demands; it is costly, takes a long time to construct, and may not solve the issues with equity and efficiency as it may only help a subset of the population. This study can positively contribute to both of these concerns by offering a viable, cost-effective perimeter metering strategy. It is also a universally applicable solution; that is, it is something that is not dependent on the current urban layout or geographical location.

It was found that there is a non-linear relationship between the inequity and inefficiency. This means that depending on the level of accumulation that the network can reach before metering occurs has an effect on the equity and efficiency. Furthermore, the non-linear relationship means that there are certain accumulations in the downtown area that can be more or less beneficial in terms of making a more efficient or equitable system. It was observed that higher accumulations tend to lend itself to less efficient but more equitable networks. It was also found that the static metering technique offers a more viable solution with regards to perimeter metering than the pump and hold metering technique if interested in eliminating inequity.

Remaining Research Questions

Although the data in this study yielded a lot of information about the effectiveness of two different metering strategies, there are several considerations that could be accounted for that were not necessarily addressed in this study. One of these improvements could include accounting for an increased complexity of the arrival rates used for experimentation. The arrival rates chosen in this study were designed to imitate different demand periods and peaks. In future experimentation, it may be beneficial to imitate more realistic arrival models, such as the morning commute bottleneck model discussed in Gonzales' (2012) study of pricing strategies.

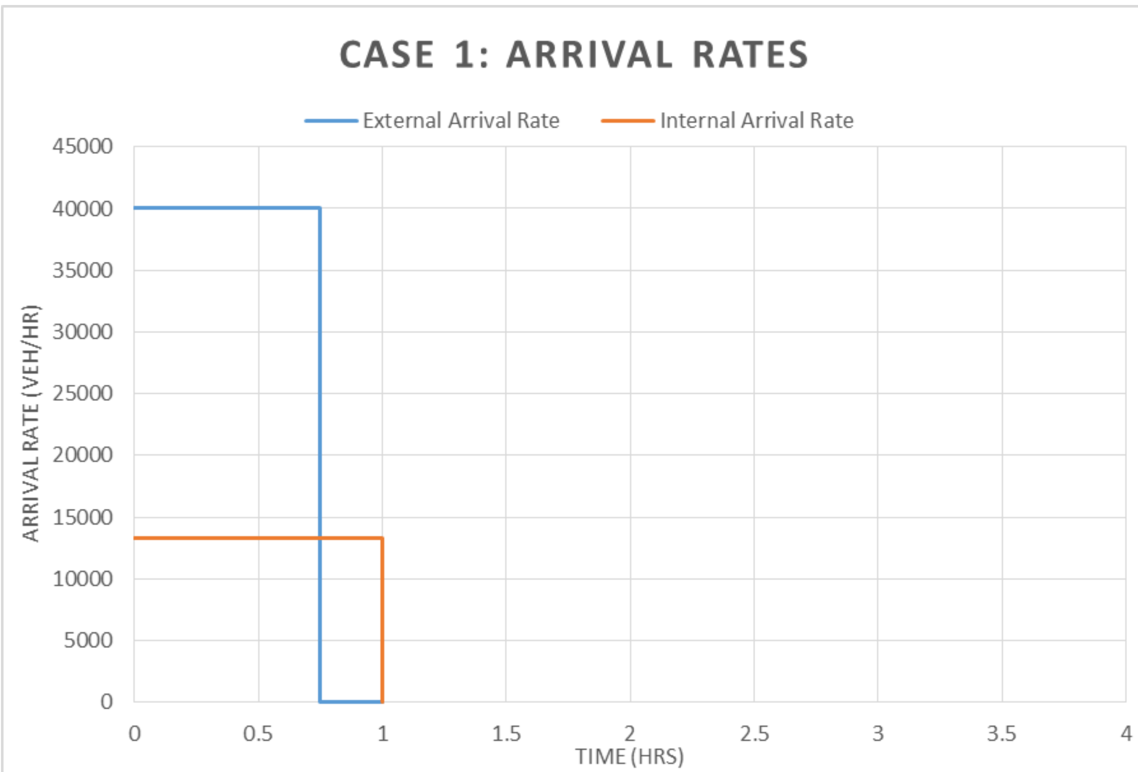
Another development that may yield interesting results is to incorporate other metering strategies into the simulations. This may lend itself to more results to compare with the data found in this study. A particular strategy of interest was similar to the pump and hold metering strategy where the downtown accumulation could reach the control accumulation. After it reaches the control accumulation, meter vehicles until the downtown accumulation returns to the optimal accumulation. Once the optimal accumulation is met, allow vehicles to enter until the downtown accumulation is equal to the control accumulation. This cyclical process occurs until all vehicles travel through the network. Based on speculation, this may be more equitable but less efficient because metering would occur less frequently and the system would be operating, more often, at an accumulation further from the optimal value. With that being said, the efficiency may offer some interesting results because having higher control accumulations allows more vehicles to enter at one time before being metered.

A final improvement would include quantifying how influential the inefficiencies and inequities are in terms of monetary losses and environmental impacts. A lot of assumptions would need to be made in terms of the types of vehicles travelling into the network from different areas of the network. With that being said, research could be performed for a case study and use geographical data to make reasonable assumptions. Quantifying the data in something other than travel time may offer more perspective on how costly additional delays may be. Along with this idea of quantifying the losses incurred because of additional delays, it may be interesting to think about how practical it may be to institute a perimeter metering strategy into an actual urban traffic network.

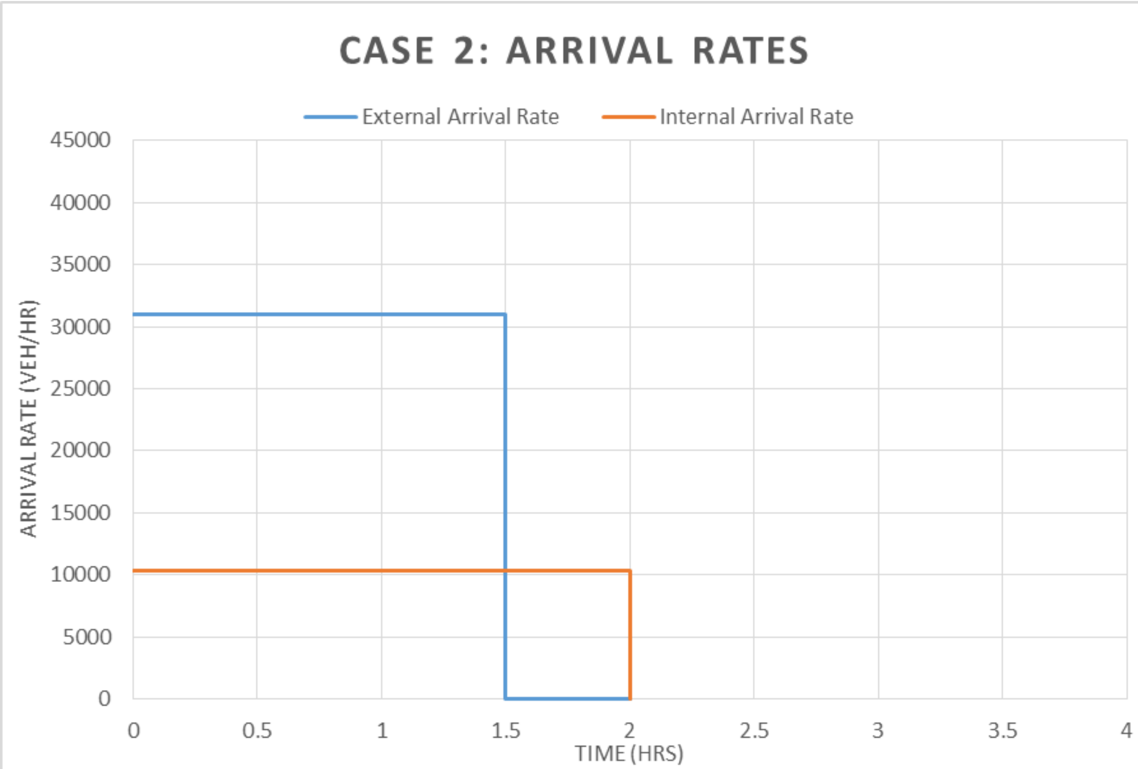
Appendix A

Graphical Representation of Arrival Rates for Six Case Studies

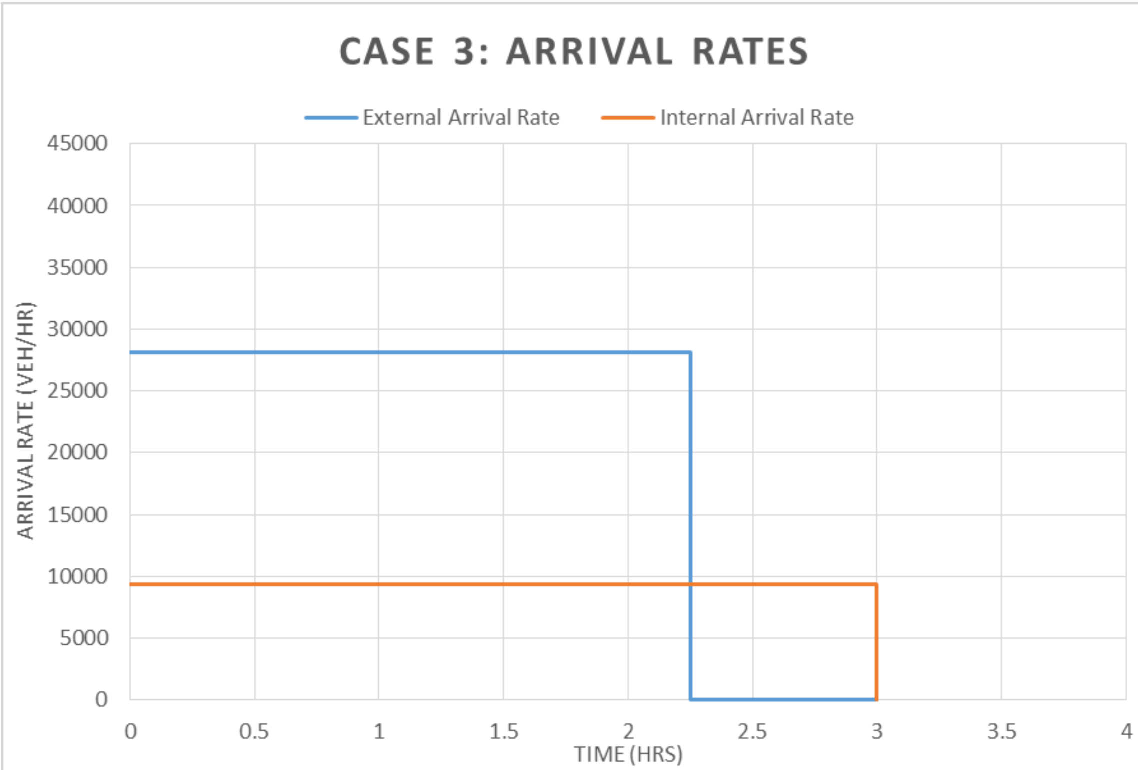
Case 1



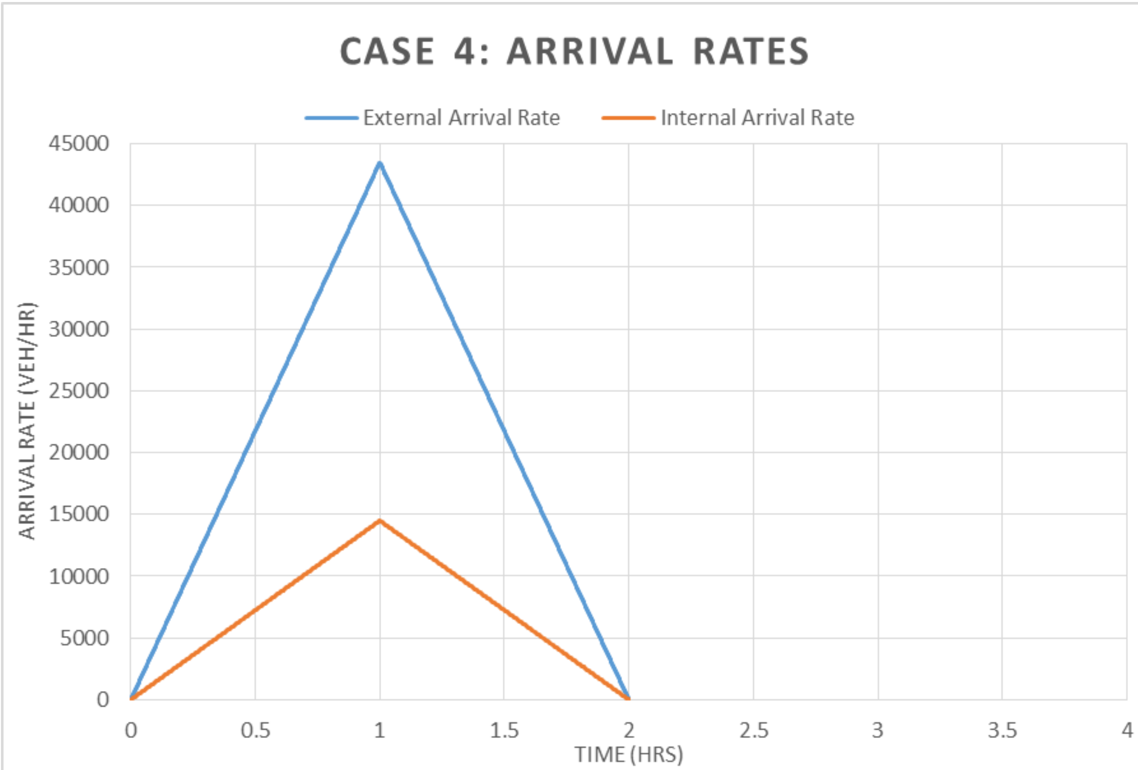
Case 2


CASE 2: ARRIVAL RATES
External Arrival Rate
Internal Arrival Rate
ARRIVAL RATE (VEH/HR)
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
0
0.5
1
1.5
2
2.5
3
3.5
4
TIME (HRS)

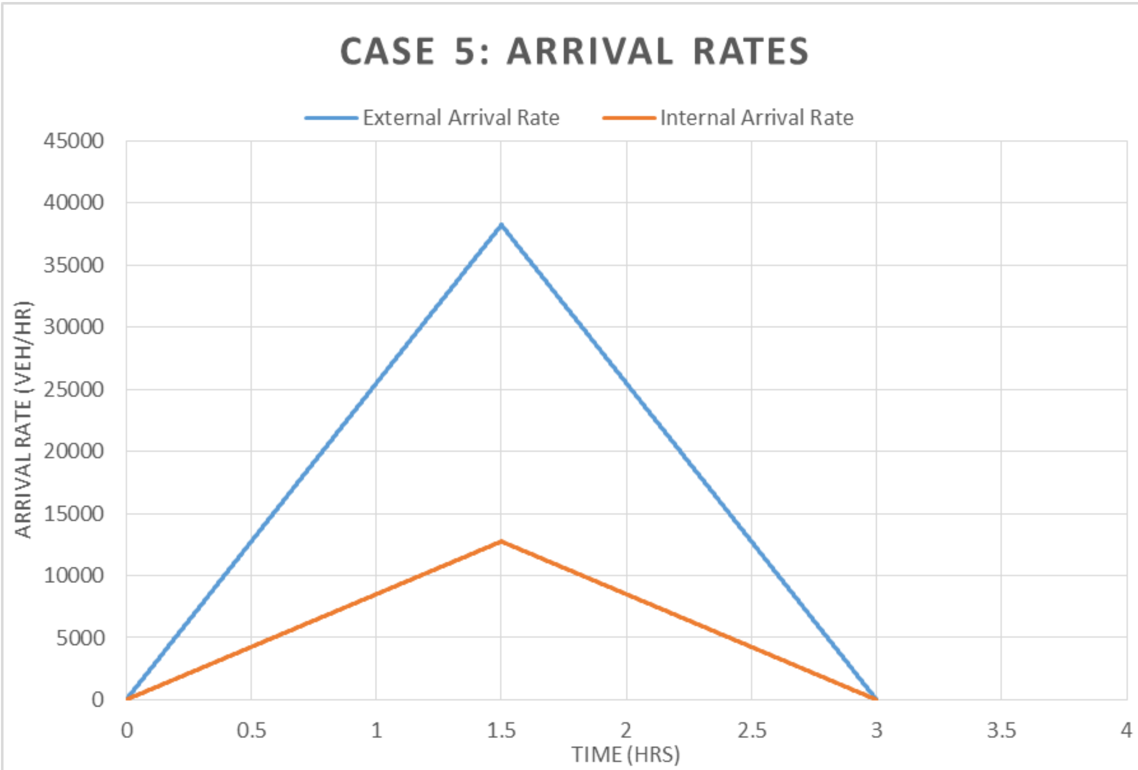
Case 3


CASE 3: ARRIVAL RATES
External Arrival Rate
Internal Arrival Rate
ARRIVAL RATE (VEH/HR)
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
0
0.5
1
1.5
2
2.5
3
3.5
4
TIME (HRS)

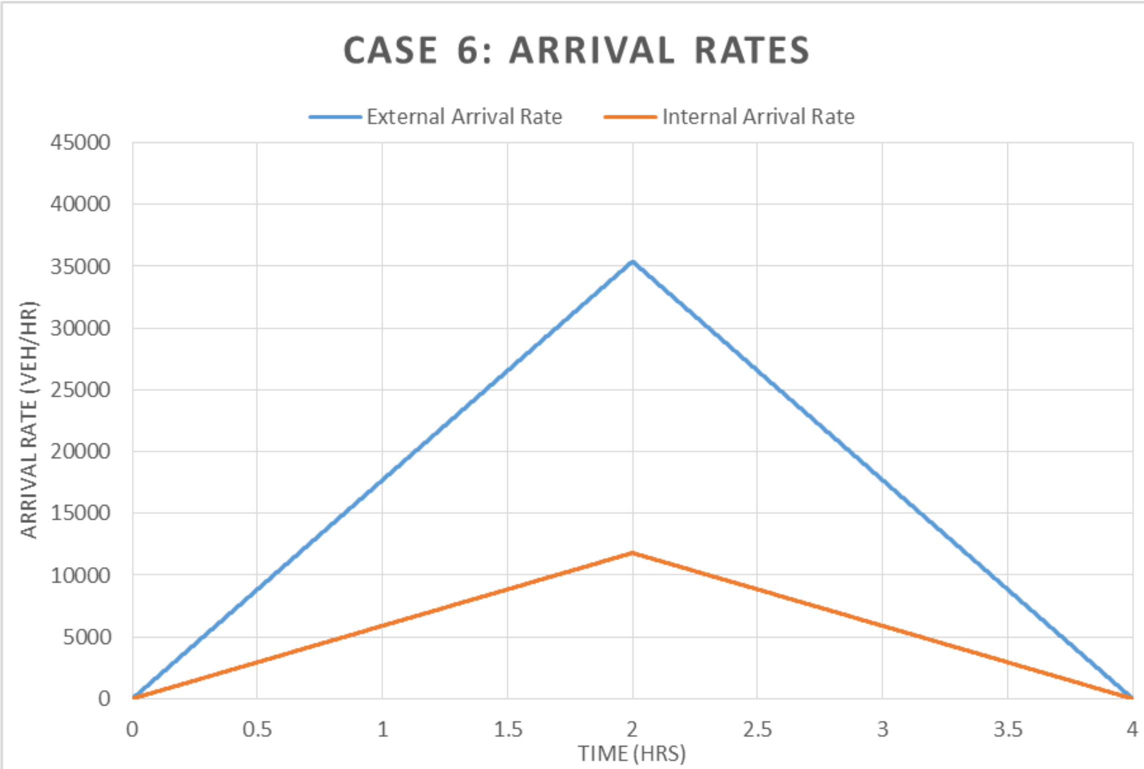
Case 4


CASE 4: ARRIVAL RATES
External Arrival Rate
Internal Arrival Rate
ARRIVAL RATE (VEH/HR)
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
0
0.5
1
1.5
2
2.5
3
3.5
4
TIME (HRS)

Case 5


CASE 5: ARRIVAL RATES
External Arrival Rate
Internal Arrival Rate
ARRIVAL RATE (VEH/HR)
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
0
0.5
1
1.5
2
2.5
3
3.5
4
TIME (HRS)

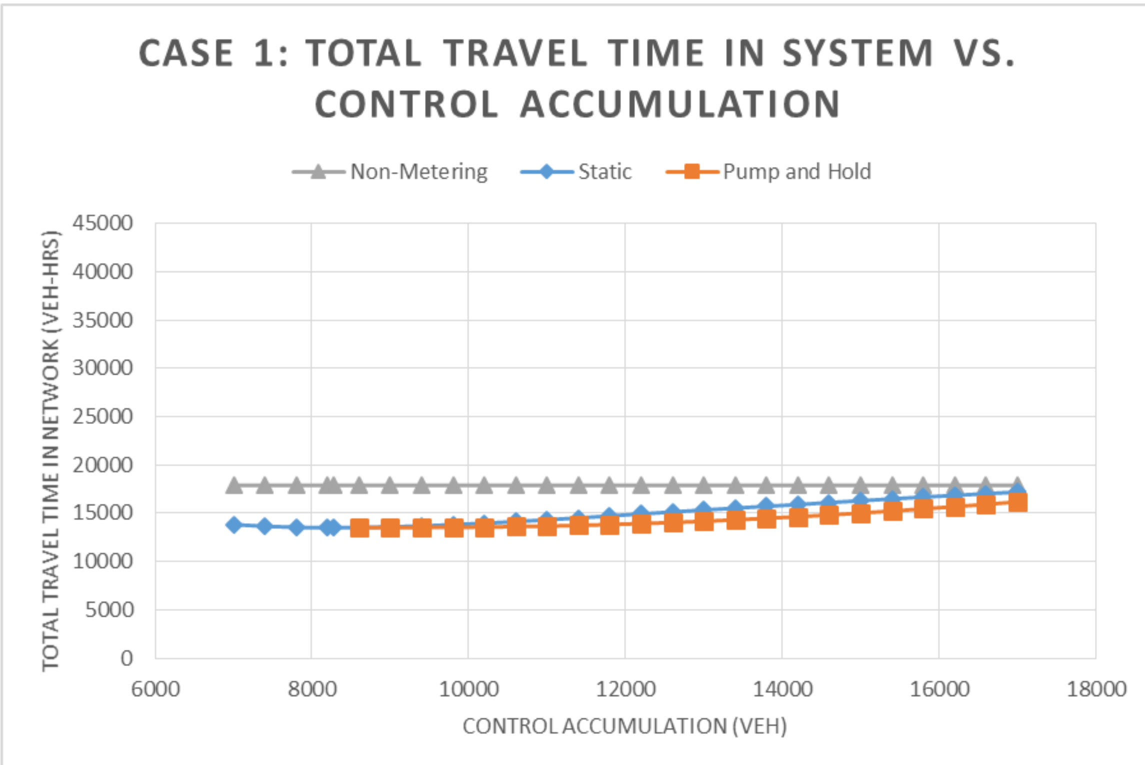
Case 6


CASE 6: ARRIVAL RATES
External Arrival Rate
Internal Arrival Rate
ARRIVAL RATE (VEH/HR)
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
0
0.5
1
1.5
2
2.5
3
3.5
4
TIME (HRS)

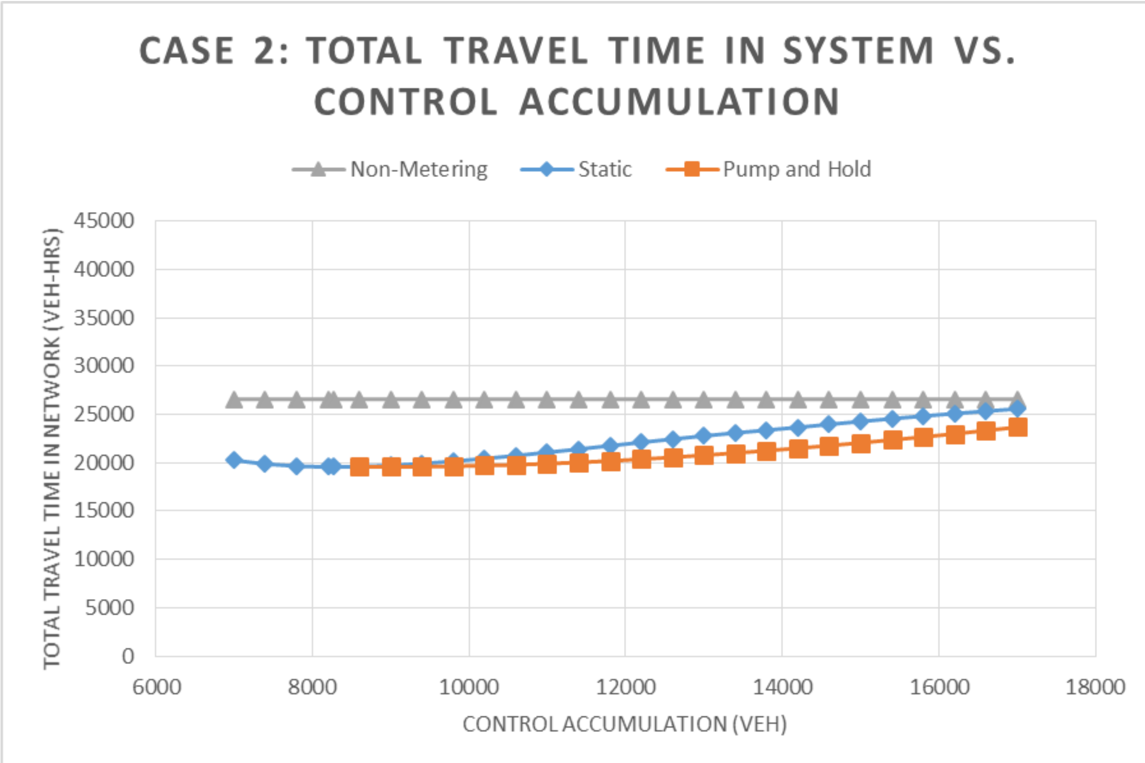
Appendix B

Total Travel Times in System at Different Control Accumulations

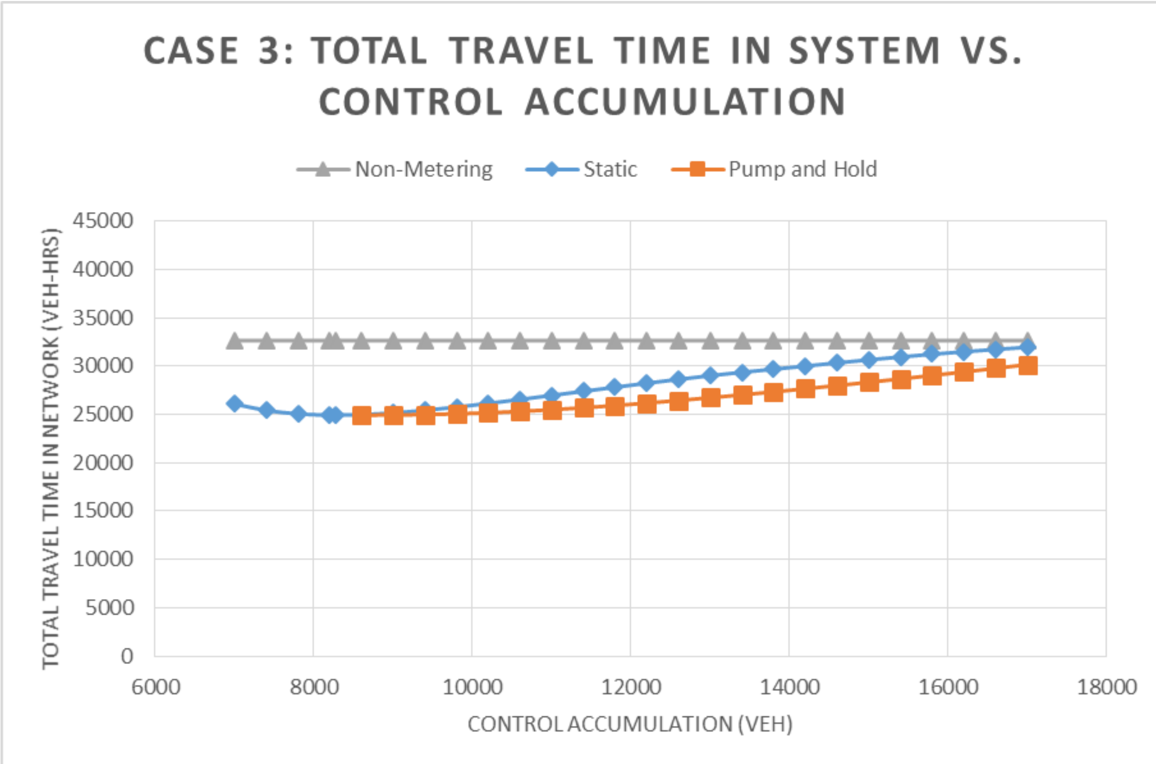
Case 1



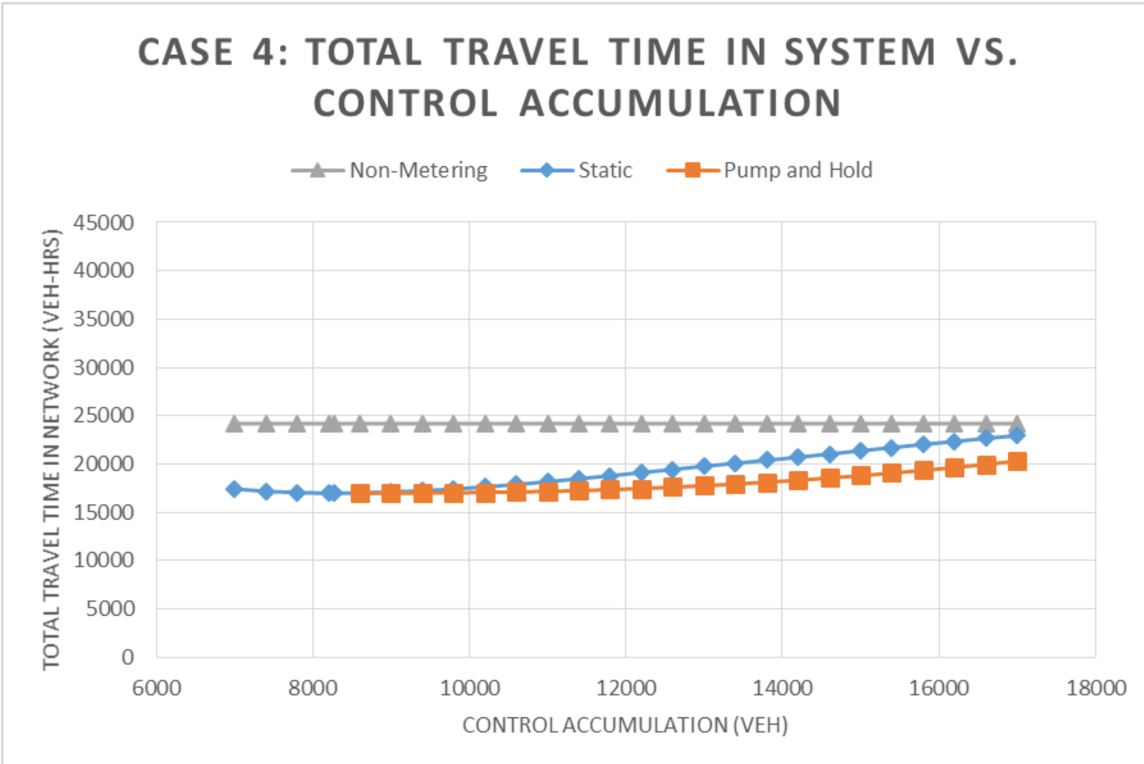
Case 2


CASE 2: TOTAL TRAVEL TIME IN SYSTEM VS. CONTROL ACCUMULATION
Non-Metering
Static
Pump and Hold
TOTAL TRAVEL TIME IN NETWORK (VEH-HRS)
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
6000
8000
10000
12000
14000
16000
18000
CONTROL ACCUMULATION (VEH)

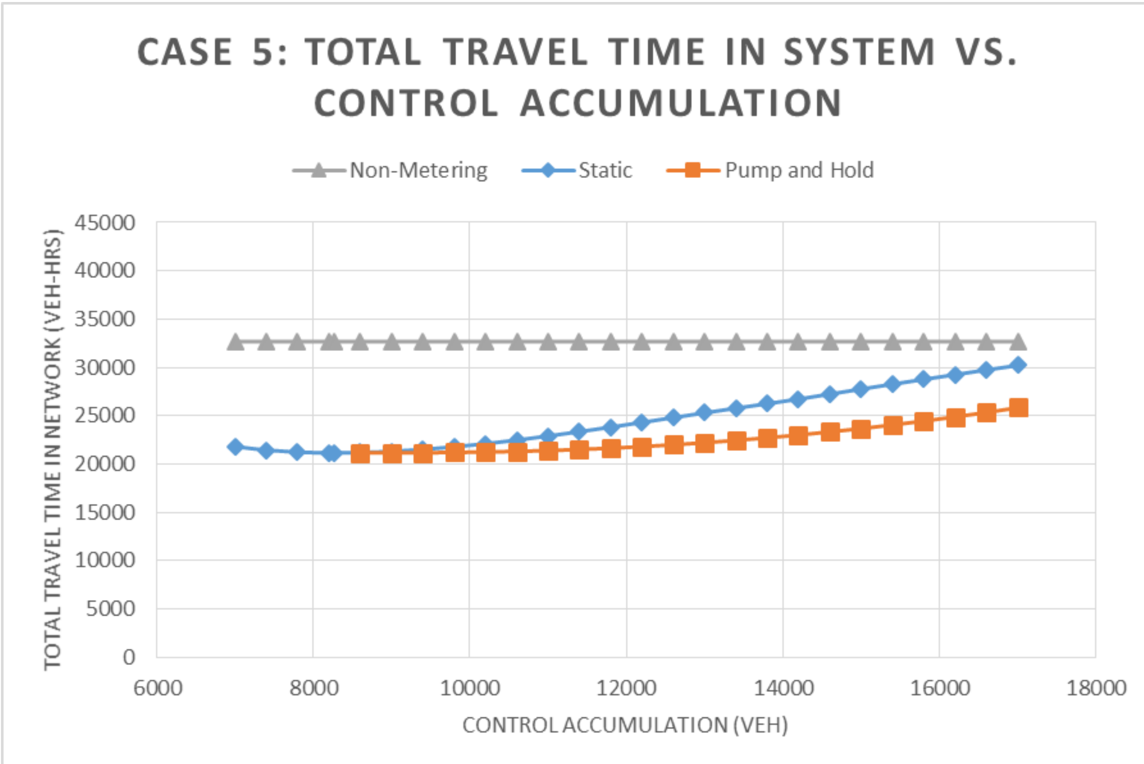
Case 3


CASE 3: TOTAL TRAVEL TIME IN SYSTEM VS. CONTROL ACCUMULATION
Non-Metering
Static
Pump and Hold
TOTAL TRAVEL TIME IN NETWORK (VEH-HRS)
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
6000
8000
10000
12000
14000
16000
18000
CONTROL ACCUMULATION (VEH)

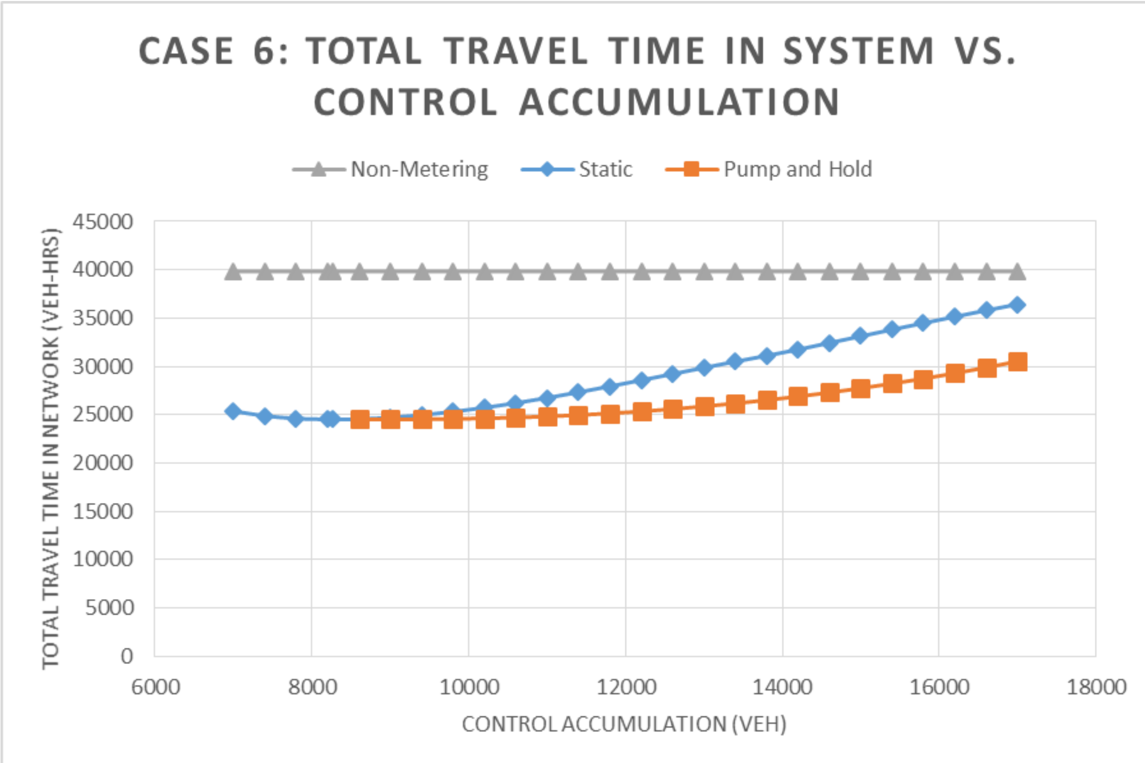
Case 4


CASE 4: TOTAL TRAVEL TIME IN SYSTEM VS. CONTROL ACCUMULATION
Non-Metering
Static
Pump and Hold
TOTAL TRAVEL TIME IN NETWORK (VEH-HRS)
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
6000
8000
10000
12000
14000
16000
18000
CONTROL ACCUMULATION (VEH)

Case 5


CASE 5: TOTAL TRAVEL TIME IN SYSTEM VS. CONTROL ACCUMULATION
Non-Metering
Static
Pump and Hold
TOTAL TRAVEL TIME IN NETWORK (VEH-HRS)
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
6000
8000
10000
12000
14000
16000
18000
CONTROL ACCUMULATION (VEH)

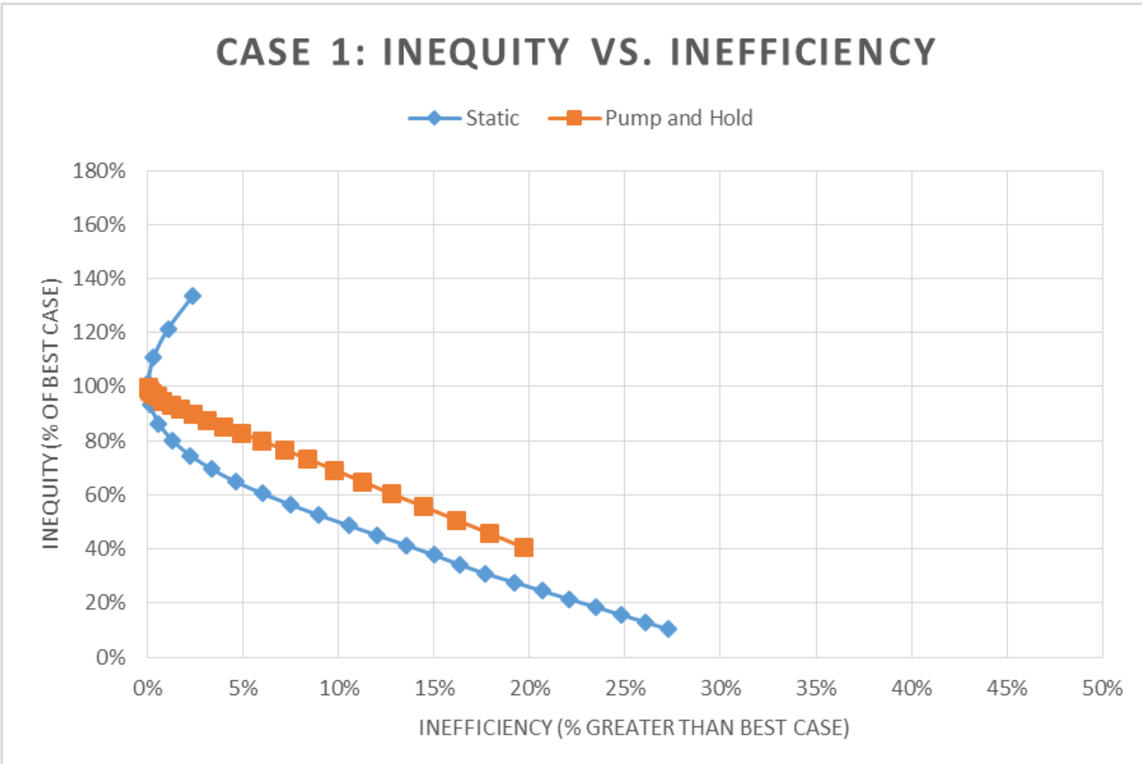
Case 6


CASE 6: TOTAL TRAVEL TIME IN SYSTEM VS. CONTROL ACCUMULATION
Non-Metering
Static
Pump and Hold
TOTAL TRAVEL TIME IN NETWORK (VEH-HRS)
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
6000
8000
10000
12000
14000
16000
18000
CONTROL ACCUMULATION (VEH)

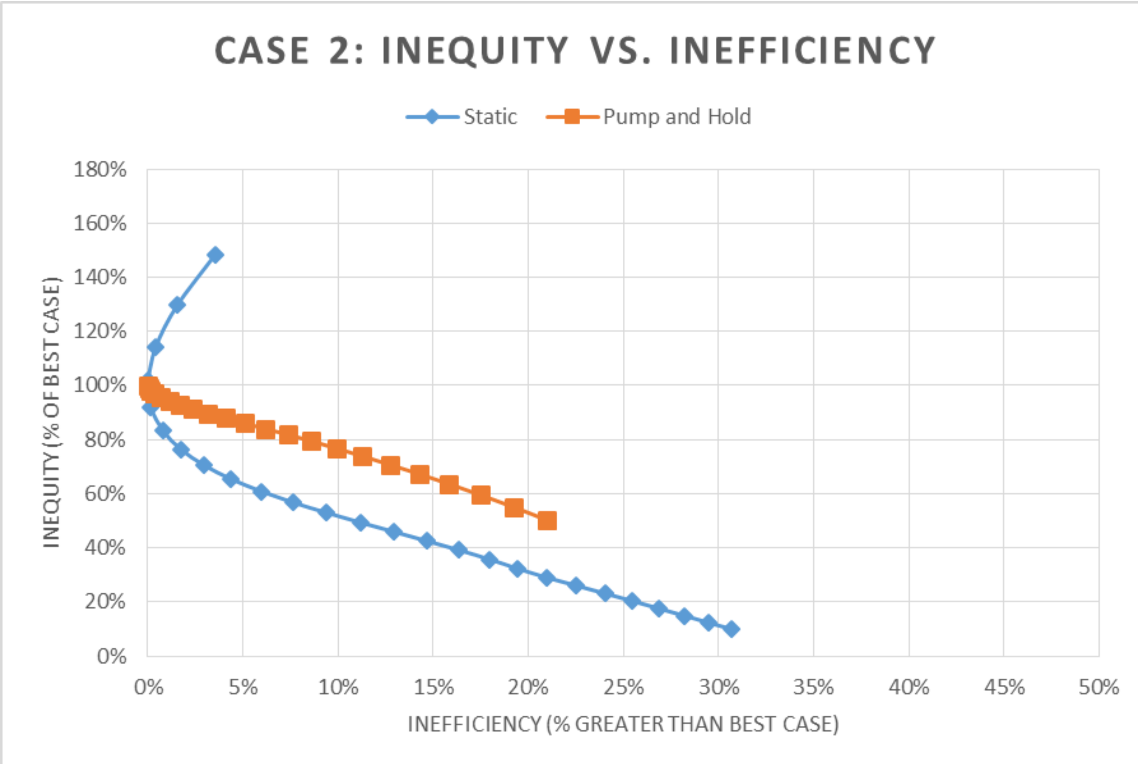
Appendix C

Measure of Inequity Versus Inefficiency

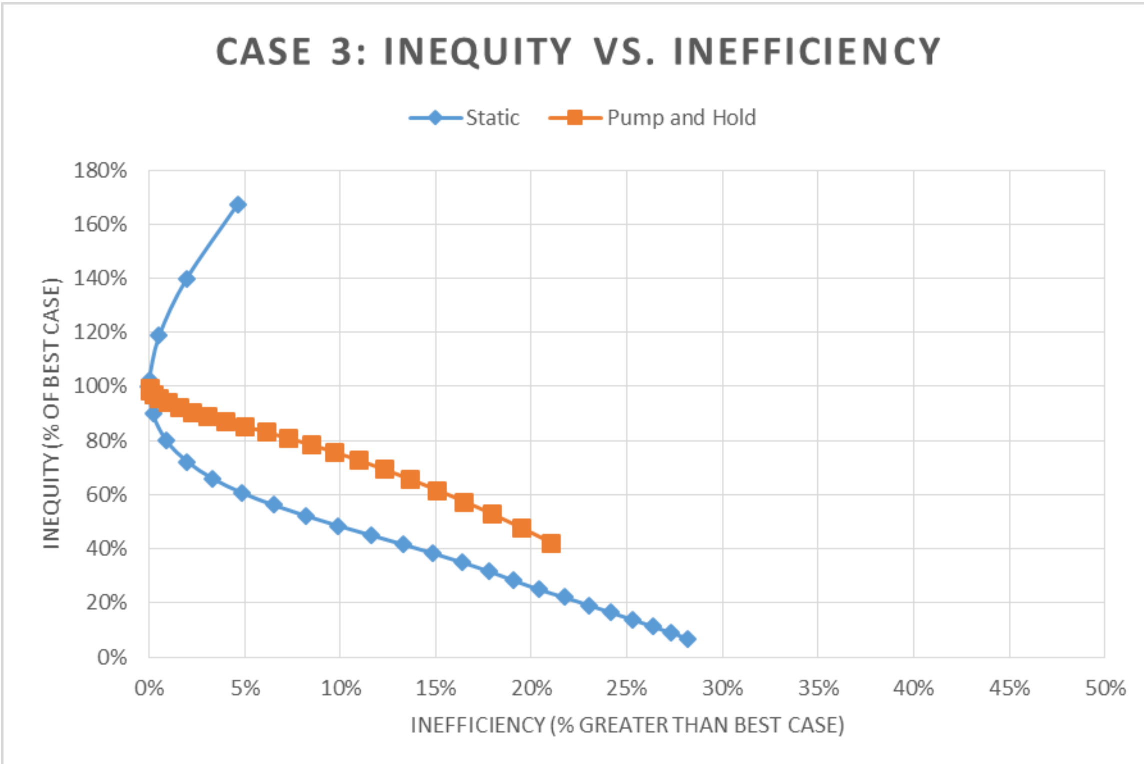
Case 1



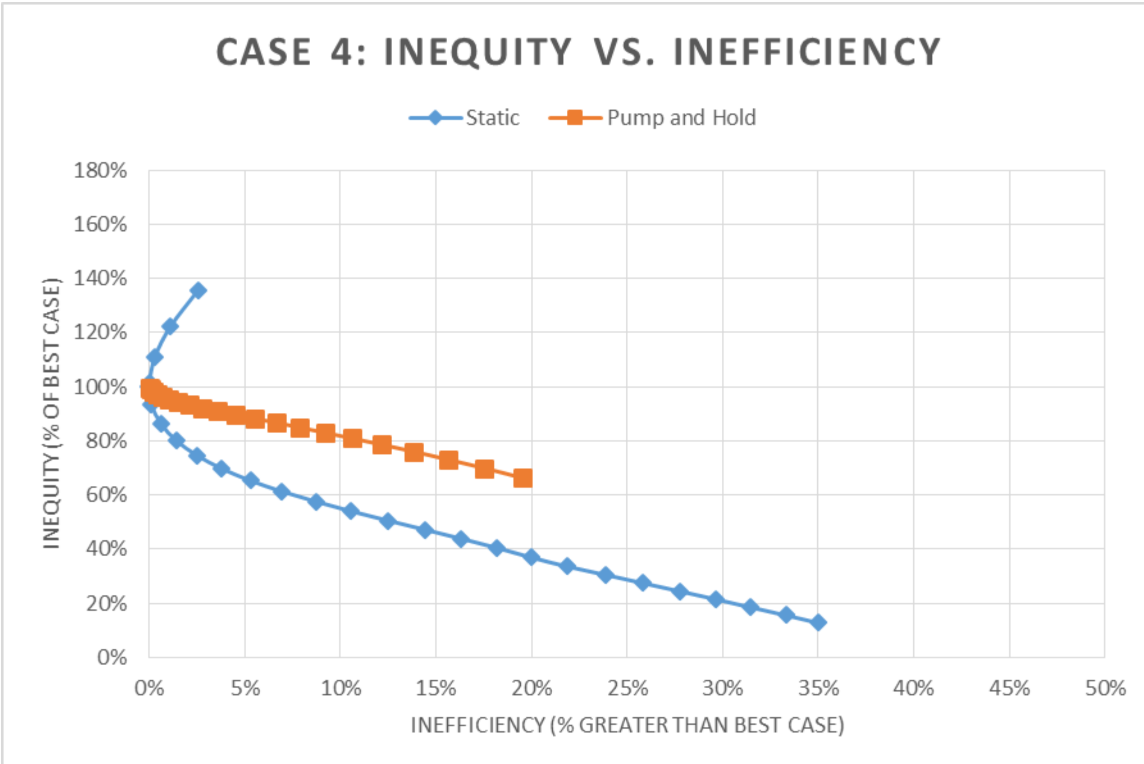
Case 2


CASE 2: INEQUITY VS. INEFFICIENCY
Static
Pump and Hold
180%
160%
140%
120%
100%
80%
60%
40%
20%
0%
INEQUITY (% OF BEST CASE)
0%
5%
10%
15%
20%
25%
30%
35%
40%
45%
50%
INEFFICIENCY (% GREATER THAN BEST CASE)

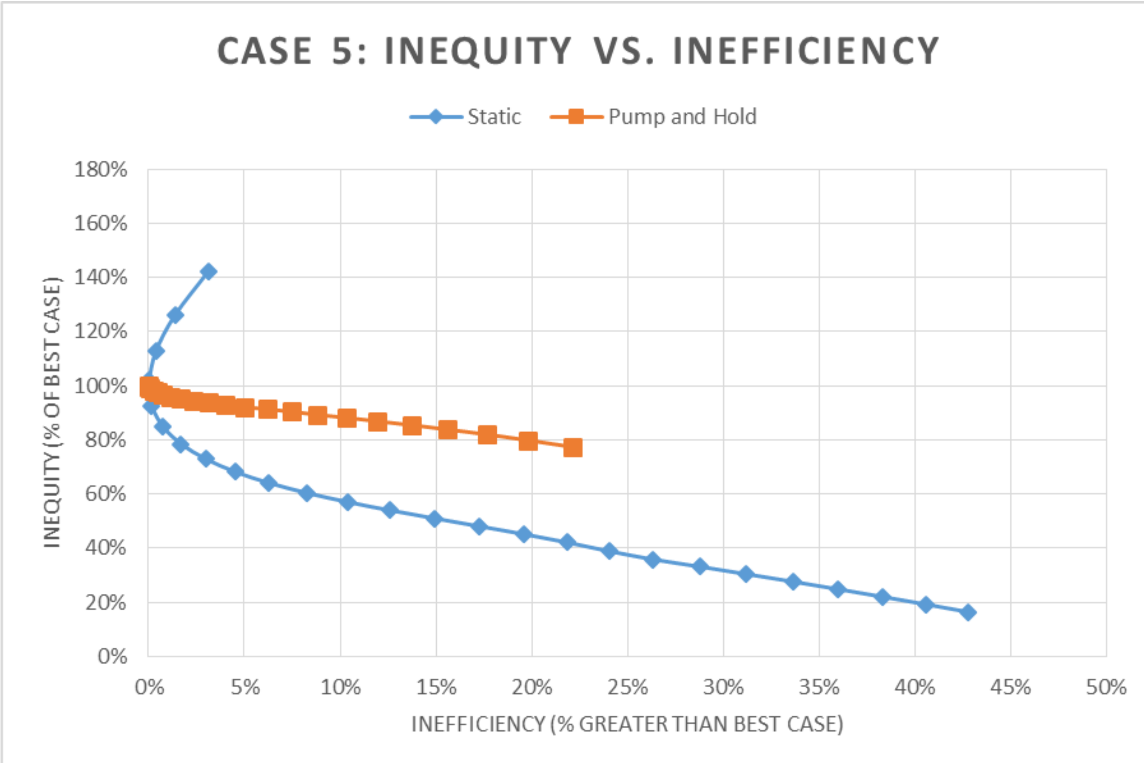
Case 3


CASE 3: INEQUITY VS. INEFFICIENCY
Static
Pump and Hold
180%
160%
140%
120%
100%
80%
60%
40%
20%
0%
INEQUITY (% OF BEST CASE)
0%
5%
10%
15%
20%
25%
30%
35%
40%
45%
50%
INEFFICIENCY (% GREATER THAN BEST CASE)

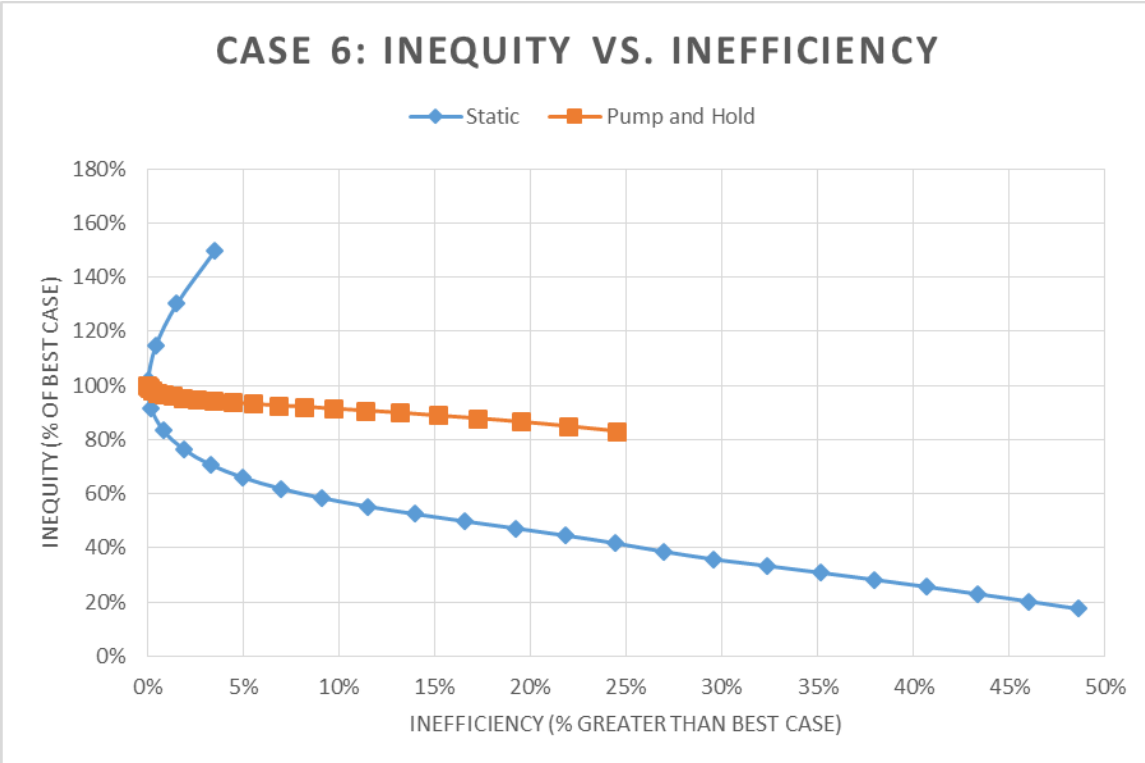
Case 4


CASE 4: INEQUITY VS. INEFFICIENCY
Static
Pump and Hold
180%
160%
140%
120%
100%
80%
60%
40%
20%
0%
INEQUITY (% OF BEST CASE)
0%
5%
10%
15%
20%
25%
30%
35%
40%
45%
50%
INEFFICIENCY (% GREATER THAN BEST CASE)

Case 5


CASE 5: INEQUITY VS. INEFFICIENCY
Static
Pump and Hold
180%
160%
140%
120%
100%
80%
60%
40%
20%
0%
INEQUITY (% OF BEST CASE)
0%
5%
10%
15%
20%
25%
30%
35%
40%
45%
50%
INEFFICIENCY (% GREATER THAN BEST CASE)

Case 6


CASE 6: INEQUITY VS. INEFFICIENCY
Static
Pump and Hold
180%
160%
140%
120%
100%
80%
60%
40%
20%
0%
INEQUITY (% OF BEST CASE)
0%
5%
10%
15%
20%
25%
30%
35%
40%
45%
50%
INEFFICIENCY (% GREATER THAN BEST CASE)

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ACADEMIC VITA

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Honors and Awards:

1. William Marciniak Memorial Award for Outstanding Achievement (Summer 2014)
2. Penn State School of Engineering Design, Technology, and Professional Programs Distinguished Student Service Award (Spring 2014)
3. Member in Penn State's Chapter of Chi Epsilon, the National Civil Engineering Honor Society (Fall 2013 – present)
4. Lean-Sigma Process Improvement Yellow Belt Certification
5. Dean's List, The Pennsylvania State University (5 semesters)

Activities:

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2. Mentor for the Engineering Orientation Network (Fall 2012 – Spring 2014)

Professional Experience:

Internship: Parsons Brinckerhoff – New York City Office (Summer 2014)

- Civil engineering experience incorporating the use of CAD programs for design-work and construction estimation

Teaching Assistant: The Pennsylvania State University

- ENGR 597C Engineering Leadership for Corporate Innovations, 3 credits (present)
- ENGR 408 Leadership Principles, 2 credits (Spring 2014)
- ENGR 409 Leadership in Organizations, 3 credits (Fall 2013 – Fall 2014)
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Internship: United States Department of Transportation (Summer 2013)

- Geotechnical research position with the Federal Highway Administration at Turner-Fairbanks Highway Research Center in McLean, VA

Internship: Pennsylvania Department of Transportation (Summer 2012)

- Project inspection at a bridge construction site within Denver, Pennsylvania