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Equitable Tolling: A Case Study on Sioux Falls

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Equitable Tolling: A Case Study on Sioux Falls

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Thesis

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Dedication

To my mom, dad, and little brother.

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Abstract

Equitable Tolling: A Case Study on Sioux Falls

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Congestion pricing is used as a method around the world to eliminate congestion in cities while generating benefits for the system in terms of revenue, reduced pollution, etc. Since the 1970s more cities around the world have adopted tolling and congestion pricing schemes. These can vary from congestion free lanes to cordon tolls to distance-based tolls, but the goal is to generate one of the aforementioned benefits for the cities were these systems are introduced. As these schemes have become more prevalent the question of how equitable they are has become more important. Many users are opposed to congestion pricing schemes because they feel that they limit their freedom. Others are concerned with how benefits are distributed with many arguing that tolls are only beneficial for the fraction of the population that is able to afford them.

This thesis is split into two parts: the first examines the history and implementation of congestion pricing schemes around the world and discusses how equity in congestion pricing has been taken into consideration over the last twenty years. The second part of the thesis is a case study on the Sioux Falls network. Several cordon tolls are applied to the network at increasing toll charges. To test whether these tolls provide an equitable alternative to the most disadvantaged parts of the population, the single-class and multi-class traffic assignment problem is solved with and without these tolls. Several measures are collected from this and an analysis is

done to determine what toll configuration provides the most equitable benefits to the disadvantaged population.

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Chapter 1: Introduction

All populated areas utilize transportation systems. Whether we notice it or not, it is necessary for our daily activities, and the more efficient and reliable the transportation system is, the higher the quality of life of its users. Whether in highly densely populated areas or places that have more land available to them, different problems with the network arise. This could range from a lack of transit issues that limit users' mobility. From roadway closures that limit access to certain areas, to traffic that creates long daily commutes, there is always a need for solutions to improve the safety and efficiency of the system.

Road pricing, tolling, or congestion pricing is a method used by municipalities and planners to manage traffic and create revenue for operations and maintenance of roadway segments. Transportation solutions seek to improve mobility and accessibility for their users but must also be profitable for the cities and firms that provide these solutions. This is where congestion pricing becomes a useful tool for transportation planners. By enforcing a charge on specific segments of the network, planners can manage traffic flow to reduce congestion in these segments and reduce trip and commute lengths within these areas to move the structure closer to a system optimal state.

Established congestion pricing models have been developing globally for the past fifty years. These models have had differing levels of success and have been implemented in distinct ways due to the advancement of technology, public acceptance, intended goal, and in some cases, government involvement. The following history of some of these systems is presented to showcase the variability of these methods around the world and the degree of success they have achieved.

The first of these methods to be widely used was the Singaporean Area Licensing (ALS) Scheme, which later became the Electronic Road Pricing (ERP) system. The nature of this system is that of a cordon toll around the city center, with additional tolls placed around highways near the city. This system relies on drivers buying a paper license and having the ability to enter the city's urban center during peak hours. In 1998, the system was replaced with an electronic toll reader that charged users when they would pass through it, making the system more efficient and faster. On a quarterly basis, the Singaporean Land and Transport Authority monitors the charges and adjusts them based on the speed at which people are traveling compared to the required speed limits. This system results in congestion levels having decreased by 15% since the change to the more modern system (Menon, 2000), with the key difference being that the drivers are charged for each trip made instead of daily. In addition, the regular revisions of the toll pricing have shown to have a significant effect on traffic and congestion levels around the city in a positive manner (Olszewksi, 2005). In Singapore, the idea of public acceptance of the tolls is more normalized than in other countries because the government has a much stronger influence on daily life. This is vital because it allows changes to the tolls with less public interference, allowing modifications more swiftly.

London implemented a congestion charge similarly in 2003. It also consisted of a cordon toll around the center of the city, with certain exemptions. Drivers of low-emission vehicles and emergency vehicles received a complete exemption from the program, residents of the area received a 90% discount, and those who signed up for electronic payment received a discount of

£1. One difference between this system and those implemented in other parts of Europe is that it requires drivers to pay for the charges on their own, which increases operational costs. The operating cost of the system is almost eight times higher than that of the Norwegian systems, totaling £80 million in 2014 (Transport for London, 2015). After the first year of operation, the toll generated a 30 percent decrease in traffic levels (Transport for London, 2014), which was then reduced to 8 percent in subsequent years.

Additionally, congestion pricing was introduced early in Norway, second only to the Singaporean system. In cities such as Oslo, Trondheim, and Bergen, the congestion pricing system has been successful and continues to be implemented. Note that the main objective of these systems is not to reduce congestion but to generate revenue for infrastructure projects. Certain tolling schemes around the country have introduced additional goals for the systems, such as reducing emissions or managing congestion. Yet, the true purpose remains to create funds for infrastructure use.

In the United States, the approach to tolling and congestion pricing has been different. In Europe, tolling was adopted in the early 1980s, but it has taken time for similar measures to implement in the United States. The country has had several periods of expansion, ranging from the 1800s, 1920s, and throughout the 1950s and 60s due to the establishment of the Federal Highway Act in 1921 and the Federal-Aid Highway Act in 1956. However, these systems were made possible by taxes instead of tolls. As time passed, the need for improvements to the infrastructure of the country became apparent, and the appeal for tolls grew because of a necessity to generate funds for the operation and maintenance of these roads. With the growth of technology, it became easier for government agencies to implement toll roads and for drivers to use as electronic readers allowing for seamless charging of the toll, while not interrupting the flow of traffic and making the cost of operating these facilities lower. As a result, systems such as High Occupancy Toll (HOT) lanes have been implemented around the country, providing a substantially congestion-free alternative to users. This method has minimized congestion whilst implementing the concept of tolling in an unconventional method compared to other systems that are operational globally. Part of the reason that systems such as HOT can be successful in the United States is because of the geography of the country and the city layouts. Given the size geographically, and with most cities lacking densely populated historical centers, there is not an obvious need for cordon tolls in many cities. This leads to solutions to congestion being geared more towards capacity expansion and allows for the implementation of tolls such as the HOT lanes. In addition, government involvement is met with more resistance in the United States, making the application of a cordon toll more difficult in cities where it could be applicable, such as New York City.

With several models implemented worldwide, congestion pricing can be a successful alternative to reduce congestion, generate funds and achieve other goals such as lowering emissions. However, there are additional issues that arise with the application of these models. In the United States, HOT lanes are sometimes known as “Lexus lanes” because many of these congestion pricing schemes seem only beneficial for the higher-income communities who can pay these tolls. The idea that these methods are not equitable has to be considered. Several questions arise from this: what are the real effects of tolls on a system, what implications do they have for different groups of people, how do we define a person or group of people’s value of time effectively to accurately model the effect of tolls, what metrics can be of use to evaluate changes to the system, and does the overall system effect represent what all groups experience or do certain areas bear the brunt of these changes to the system.

The purpose of this thesis will be to find a way to answer these questions for a specific type of network. Initially, equity will be explained through the scope of congestion pricing, as the chosen definition and principle of equity can significantly shape the tolling system's objective of fostering a fairer outcome for all parties involved. Then, the implementation of various cordon tolls on the Sioux Falls network will be analyzed at the system level, with regards to specific links, and by splitting the population into classes based on income. The results of these tolls on the system are then evaluated to determine if these methods can reduce the Total System Travel Time (TSTT) gap for lower-income classes, while maintaining a reasonable increase in Total System Cost (TSC).

1.1 Background and Overview of Current Literature

Congestion is a problem that occurs worldwide, affecting people's commutes, businesses, causing lost time, and worsening the quality of life of those that experience it daily. As a result, there is a wide literature on policy, implementation, novel techniques, and real-life studies on the topic.

The costs caused by congestion reflect, in part, the delay that other drivers experience due to a vehicle trip (de Palma and Lindsey, 2011). Pigou was one of the first to mention congestion pricing, suggesting that there should be a tax on congestion in his book *The Economics of Welfare*, (Pigou, 1920). Thus, the costs incurred by congestion result in significant costs in travel time, fuel consumption and monetary value.

The Routledge Handbook of Transport Economics defines congestion pricing as "a charge that makes driving costs better reflect the time loss a car trip causes other drivers." This would mean that a congestion price should adjust for the time delays created by network users. The application of a charge will have significant impacts on network users as it will force them to change the way they move regarding trips made, destination, type of transport used, time at which the trip is made, and other decisions. Additionally, it will affect important life decisions with regards to living situations, proximity to work, and where to do business.

As mentioned before, there are congestion pricing schemes in several large cities around the world: London, Singapore, Stockholm, Oslo, and the use of HOT lanes in the United States. In addition to these, a cordon toll is to be implemented in New York City in 2024. Some of these have the goal of reducing congestion, and others have the aim of generating revenue or reducing emissions within their cities, with all these systems having shown success in terms of reducing congestion and generating revenue for their respective cities.

In their review of congestion pricing, de Palma and Lindsey list four methods as the most widely used: facility-based, cordon tolls, zonal schemes, and distance-based schemes. Their differences and applications are summarized in the table below.

Table 1: Congestion pricing schemes and their features. (de Palma and Lindsey, 2011)

Congestion Pricing Scheme	**Features**
Facility-Based	These types of tolls are applied on tunnels, bridges, or road segments. They are the most common type of congestion pricing. The idea is for users that pay these tolls to travel in a congestion-free facility.
Cordon Tolls	Cordon tolls impose a fee on drivers for entering or exiting a specific zone within a city. This fee can be in one direction or in both, and the charge varies from a daily charge to a charge per passage depending on where it has been implemented. Several of these tolls have been focused on generating funds or decreasing emissions instead of reducing congestion.
Zonal Schemes	These are also known as area charges. They charge users for entering or exiting a certain area. The boundaries for the area can be natural elements, such as lakes, rivers, forests, or man-made elements such as bridges, tunnels, and roads. Driving along the perimeter of the zone is usually free.
Distance-Based	These schemes charge users based on the distance that they travel, with the charge being nonlinear or linear. They are usually implemented on heavy vehicles. The goal is to recoup the cost on the roadway incurred by these vehicles.

On top of varying the type of scheme that is implemented, the payment type can vary by type of vehicle, weight, and number of axles. This is frequently seen in facility-based schemes, where larger vehicles tend to pay a higher fee. For area schemes and cordon tolls, tolls will usually only be paid during a certain time of the day, being either peak hours or most of the workday. For these schemes, some cities implement a flat fee with a cap on the maximum that a vehicle can be charged per day or per month. Others charge per user every time they enter the area or pass through the cordon. There are also tolls that will be adjusted based on the current congestion to maintain free flow or near free flows speed on the network. This is commonly seen in facility-based schemes and HOT lanes.

Tolling facilities and congestion pricing schemes require technology for the system to operate. The main factors that need to be enforced are identification of vehicles with regards to weight, distance travelled, license plate or number of axles, a method to effectively charge users, and resources to ensure that the charges are being applied (de Palma and Lindsey, 2011). These functions can be done manually or through Electronic Toll Collection (ETC) systems. When done manually, users pass through the toll facility, pay, and are allowed to pass once payment has been made. The downside of these manual facilities is that they increase operational costs and slow down traffic. Many of these systems are being replaced with ETC systems to make the toll collection process more efficient and maintain free flowing traffic.

The types of ETC systems available fall into the following three categories: roadside systems that use Automated Number Plate Recognition (ANPR), Dedicated Short Range Communications (DSRC), and systems placed inside of vehicles that use satellite or cellular networks (Noordegraaf et al., 2009). ANPR will document the license plate and number of the vehicle. DSRC relies on antennas above readers and tags on vehicles to check for a vehicle's passing through the reader. Satellite and cellular readers are less developed and used than the two previous systems, but they rely on GPS or cellular networks to locate the vehicle and can be used for distance-based schemes. The advantage of cellular over GPS is that the signal is not affected by infrastructure such as high rises and tunnels. Conversely, it could also be said that cellular systems must rely on the proximity of a cellular network near the roadway for it to be used effectively.

The literature on congestion pricing is vast. Due to the social equity implications of congestion pricing, much of it is about the equitable implementations of these systems, with some suggesting frameworks to include social equity in transportation planning. Many studies also focus on the citizens’ perspective on congestion pricing and how approval for these schemes changes before and after they are implemented. There are also a lot of case studies on the various methods employed around the world, evaluating their efficiency and other metrics. Finally, a lot of research focuses on finding optimal tolling schemes in terms of network performance. This review will summarize relevant findings on these topics.

1.1.1 Equitable implementations

Studies focusing on the equitable implementation of congestion pricing schemes usually compare the current situation to the proposed changes made with the new scheme. Ecola and Light (2009) note that there are not many studies focusing on the effects of congestion pricing in the long-term horizon regarding equity. Singapore would be the best option for a study of this type because congestion pricing has been in place for more than fifty years, but there were no equity-focused studies found on the Singapore system in the literature. Evans (1992) notes that lower-income groups of the population will most likely suffer less from congestion pricing as they tend to use public transit more than higher-income groups. This helps ensure that toll revenue is used for improvements in transportation infrastructure, which can be a way to make tolling more equitable. Ecola and Light (2009) also point out that many studies compare congestion pricing to an unchanged network, when if no tolling policy is implemented, infrastructure and capacity expansion will be needed. This suggests that it would be more appropriate to compare congestion pricing schemes to capacity changes in the network.

Looking at specific types of tolling schemes, it was found in a study of three cordons in the United Kingdom that the cordon toll could range from being progressive, to neutral, to regressive, based on the location and the geographic distribution of income in the region (Santos and Rojey, 2004). This is in consensus with what Parkhurst et al. (2006) concluded with their findings, also suggesting that the effects of the cordon can be equitable based on its proximity to lower-income neighborhoods. In addition, the question of how to charge a cordon has been tackled by comparing a cordon where drivers are charged for entering versus a zonal scheme where users pay once to drive inside the area. The results showed that the difference in the Gini coefficient between these plans was minimal.

The consensus regarding HOT lanes is that they have less of an impact on equity than other congestion-pricing schemes. The reasoning behind this is that they do not limit accessibility to users, as other uncharged lanes are available to users of the network. In terms of equity analysis of these lanes, Eichler, Miller, and Park (2008) looked at the implementation of three HOV lane systems in Washington D.C., finding that these systems would provide equity benefits for protected populations. The benefits they found were measured in terms of access to jobs.

Finally, some researchers have proposed frameworks for including equity into transportation policies. Two examples of this were found by Ng (2005) and Behbahani (2019). Ng’s framework proposes the following steps:

1. Identify protected groups
2. Locate protected geographic areas with the help of census data
3. Determine the degrees of disadvantage in each of the aforementioned geographic areas, with five levels of severity
4. Pinpoint where essential services and destinations are located (hospitals, schools, transit stations, highways)
5. Assess transportation projects on how they affect accessibility between the protected populations and the location of essential services and destinations

Behbahani focuses more on the implementation of social equity theories:

1. Calculate what the costs and benefits relevant to the project will be
2. Classify groups of importance based on several factors (race, age, ethnicity, disability, etc.)
3. Select an equity approach based on different types of equity and social equity theories.

Both frameworks include selection of target groups. Behbahani focuses on the use of social equity theories as guidance and justification for equity in projects, while Ng includes equity into transportation plans by specifically noting how accessibility to essential services change for disadvantaged groups due to the changes.

1.1.2 Opinions on Congestion Pricing

Perspectives on congestion pricing and tolling schemes around the world are a key part of the implementation process of these systems in various cities. Referendums, public hearings, and test trials are usually part of the process to achieve public approval for congestion pricing. People commonly have justifiable concerns about the implications these new systems will have on their daily commute, quality of life, and the project's effectiveness. Equity is also of concern for various groups, especially minorities, people with disabilities, and lower income individuals. Because public support for congestion pricing is needed in most parts of the world for its implementation, it is important to conduct surveys that gauge current opinions.

Zmud (2008) performed an overview of studies gauging support and opinions for road pricing. Of 103 studies, 56% showed majority support for these plans, 31% were against, and 13% did not report a majority in favor of any of the former. Studies were also classified into project type and context of project. Regarding the context of a project, some surveys would ask about specific projects, while others just asked about a general opinion on the concept. Support for specific project surveys was around 62%, with less than half of respondents being in favor of tolling in general surveys. Interestingly, most respondents supported projects involving HOT lanes, facility tolling, and congestion-free lanes, but cordon tolls and privately-owned tolls elicited mostly negative opinions from those surveyed. Finally, Zmud found that there were several ideas and items in the surveys that resulted in people backing congestion pricing: benefits, questions on specific projects, revenue use, equity, detailed explanations, simple schemes, and previous exposure to tolling.

Podgorski and Kockelman (2006) analyzed the opinions of Texas residents on poll roads. They surveyed 2,111 people, with an almost equal share of individuals coming from six large cities and the remaining being from all over the state. Questions were asked on a variety of topics: transportation, how toll revenue would be handled, equity, tolling systems, charges, and how these projects would be funded. There were several important results from the study. Texans favored the improvement of current roadway before investing in new infrastructure. Most respondents were against paying tolls for already built roads, and a small majority also favored not paying tolls on newly built roads. Residents of larger cities were more likely to favor or be aware of tolling projects. All regions surveyed thought that toll roads are not as fair as other measures, with some regions having a larger portion of respondents in agreement with this statement. Finally, there were mixed results regarding gas taxes versus congestion pricing. There was no overwhelming support for either of the two with almost all regions being slightly in favor of the second option.

Romero et. Al (2020) focused on Madrid and its citizens' opinions towards tolling. This survey proposed four different alternatives to users of a specific corridor that currently allows drivers to use a toll road, highway, or transit to travel. The options available to respondents consisted of a fixed fee, charge reductions for vehicles with more passengers, a new faster bus route and a reduction in transfers for the transit service. The results were overwhelmingly in favor of the two proposals that would implement changes to the transit facilities to make them more efficient. Amongst the tolling options, the fixed fee received more support than the charge reductions for vehicles with several passengers, but neither received major support. These results are not surprising as the authors point out that the toll road was already not frequently used and that carpooling is not popular in Spain, thus making these options unappealing.

In more recent years, Glavic et. Al (2020) surveyed people in North Macedonia, finding that distance-based pricing was preferred for daily highway users, while time-based pricing was preferred for less frequent highway users. Odeck and Kjerkreit (2010) studied opinions on congestion pricing in Norway. Using data from surveys completed by the Norwegian Public Roads Administration, they found that those surveyed thought negatively of both current and planned tolls, with this shifting slightly after the implementation of the toll. Similar to Zmud's findings (2008), there was an increase in positive opinions when surveys provided accurate information on projects and the benefits they will provide. In China, Xianglong et. Al (2016) surveyed 897 vehicle users about a hypothetical congestion pricing scheme in Nanjing, consisting of an area-scheme that would charge users on weekdays during peak hours. Their responses showed that on average, respondents were aware of issues in the city (congestion, contamination, noise), but did not believe that the proposed scheme would be particularly fair to them or others and thought that it would affect their freedom to choose a mode of travel.

1.1.3 Case Studies

Case studies are an effective method to analyze the effectiveness of various congestion pricing measures worldwide. They provide real world data on the impacts and benefits that these measures have on the general population. Additionally, successful case studies provide evidence and support for these measures when they want to be implemented in different countries.

Eliasson and Mattson (2006) performed a case study on the Stockholm system. Their analysis focused on the cordon lines in the city. The first wraps around the city center, and the second divides the north and south of the city using Lake Malaren for division. Cars are charged 15 Swedish Krona (SEK) during peak hours and 10 SEK during off-peak hours, with charges being bidirectional. The study found that the values of travel time for low, medium, and high-income groups decreased by slightly more than 1%. Higher-income users paid more due to higher usage of personal vehicles. Finally, a proposed scheme where the charges were used for transit revenue provided the most benefits for low-income users and provided a small negative impact on high-income users.

As mentioned before, the London congestion pricing scheme consists of a cordon around the main downtown area of the city. Lehe (2019) looked at the impacts of this scheme. Between its implementation and the end of 2007, the entrance of personal vehicles to the zone decreased significantly, while the use of taxis and bicycles increased. Since 2008, the use of private vehicles has continuously decreased as people have resorted to using ride-hailing apps within the area, such as Uber (Transport for London, 2017). Road charging options for London (ROCOL) provided estimates of the cost for the system to be around £30 to 50 million, with costs to set up the whole system, including projects that helped users adjust to the system reaching £162 (Transport for London, 2007). Despite the high initial costs, TfL's reports have shown that the system has become profitable, with profit rising from £78 million in 2003 to £164 in 2016.

The Milan Ecopass/Area C provides an interesting case study because its nature is different from other congestion pricing schemes implemented around the world. First, Milan and other Italian cities already have vehicle-limited zones, Zona a Traffico Limitato (ZTL), near the historic centers of the city. Secondly, the city chose to implement a scheme that has a focus on reducing emissions from vehicle-use to counter exceedances of the limit set by the European Union on the former. The charges are in place from 7:30 A.M. to 7:30 P.M in an area called Cerchia dei Bastione, located around the city center. In this area, payments are required daily, with three different charging options depending on the type of vehicle. Regular vehicles pay €5, residents pay €2, and service vehicles pay €3. Additional exemptions are in place for residents (Lehe, 2019). The initial implementation of the system saw a reduction in vehicles entering the area, with an overall 14.4% decrease in vehicles entering, but only a 3.4% reduction in city-wide traffic (Lapsley and Giordano, 2010). With regards to emissions, there has been a reduction in the number of days where emissions were over the threshold of 50μg/m^3, down to 102 days in 2008 after having more than 148 days on average before this. The average concentration of PM10 has also decreased to 44μg/m^3 (Corriere della Sera, 2008a). Despite this, there is a divided opinion regarding whether Ecopass/Area C has had the desired effect on the city's emissions (Lehe, 2019).

In the past 30 years, HOT lanes have been implemented in different parts of the United States and Canada. Supernak (2005) looks at the effects of HOT lane on I-15 in San Diego, where the objective was to generate funds. This system is implemented on a stretch of 8 miles where High Occupancy Vehicle (HOV) already existed. Thus, vehicles with 2 or more passengers may still use these lanes at no cost; other users must pay a charge to use the lane adjusted in real-time to maintain a Level of Service C within these lanes. Throughout the first three years of the program, from 1996 to 1999, the number of users on the express lanes rose from 10,000 vehicles to 16,000 vehicles daily. Supernak (2005) also found that these changes resulted in a changed distribution of traffic during peak periods. The number of vehicles during peak periods increased but was kept below LOS C. Plus, the maximum values of vehicles on I-15 during the peak hours changed from one peak to two peaks, resulting in a changed distribution of maximum traffic volumes during rush hours.

1.1.4 Optimal Tolling Schemes

Optimal road tolling has been studied for a long time to find the best methods to improve current systems. Dafermos and Sparrow (1972) focused on the resource allocation problem with regards to a network governed that is "user optimized" instead of managed by a transportation agency. Their improvements to the network were made at user equilibrium (UE) and they found a travel time that corresponds to "each traveler paying the correct price for the amount of travel purchased."

Yan and Lahm (1995) developed a bilevel optimization formulation to find optimal tolls on roads. Their formulation does not try to achieve system optimum, instead it works as a sort of Stackelberg game, with the toll controllers serving as leaders and the users as followers. The controllers can affect route choice with their policies, but users still have freedom to choose the route that best suits them. By adding a constraint that considers the network's capacity to handle demand, as queues form when demand exceeds capacity, they formulate the traffic assignment problem with queueing. Sensitivity analysis is used to find how the network equilibrium with queueing will react to toll changes. This is then applied to find the optimal toll for different objectives; maximizing revenue and minimizing travel time.

Second-best congestion pricing is another topic that has also been studied. It is a problem where not all the links in the transportation network can be tolled. Verhoef (2002) argues that this is a more practical tolling problem because unlike first order, tolling of all links to account for marginal external costs, can be adapted to practical schemes that either for political or funding reasons cannot toll all links in the network. He developed an algorithm that derives optimal tax rules for this problem, with the constraint specific to the second-best tolling problem being that tolls are set to maximize social welfare which he defines as the difference between total benefits and costs. Results testing on a small network found that after a couple of iterations the second-best toll is very close to being reached.

Research has also been done on dynamic tolling schemes, which adjust charges to vehicles to maintain desired flow characteristics on the tolled facilities. This research has more applications to HOT lanes which tend to offer a congestion free option to drivers. HOT lanes focus on maintaining free flowing traffic in the facility and to maximize the vehicles passing through tolled facilities to ensure total delay to the system stays at a minimum (Lombardi et al., 2021). Laval et al. (2015) applied the dynamic traffic assignment problem to a network with dynamic tolling implemented. Linear pricing strategies for the HOT lanes are determined, which allows them to optimize any objective required such as: revenue maximization or minimizing emissions while managing traffic as long as the ratio of delay of untolled to tolled lanes does not surpass a given value. Zhang et al. (2008) created a dynamic congestion pricing algorithm that dealt with issues that they found with previous congestion pricing schemes regarding the length of time to update the toll and the amount to change the charge by. Applying feedback control theory, a piecewise function of the traffic speed is used to then calculate the optimal toll rate with a logit model. Simulations on HOT lanes were performed and confirmed the validity of the algorithm at keeping the system operating under different demand values.

Chapter 2: Equity in Transportation

With the passing of time, equity has become increasingly important in transportation planning and development of projects. Planners and policy makers have sought to implement projects that provide reasonable benefits for all groups and social classes without being detrimental to any one of these groups. With this new approach, there has been a shift from schemes that look to just minimize congestion. Many new transportation policies focus on decreasing emissions, improving accessibility for the system and its users, and reducing the inequality gap within the system. But the focus on implementing equitable policies creates several challenges in the policymaking and modeling processes. Many of these challenges stem from the lack of a universal definition of equity and set guidelines that can be followed to accurately measure and model the effect of suggested policies.

This chapter will give an overview of the process that goes into determining equitable policies in transportation. To start with, different types of equity will be discussed in general and regarding transportation. Following this, social equity theories will be explained with the goal of giving the reader an idea of how both the types of equity and equity theories can have a large impact on how a problem is modeled and what is classified as inequitable. The data collection process will be discussed, as once again, this is not clearly defined by the authorities, and it creates uncertainty and disparity regarding whom these transport policies must benefit, and the units of analysis used will be addressed to explain how the improvement in equity is measured. Finally, a discussion of the general population’s attitude towards congestion pricing and its effects on the implementation of these policies will be discussed.

2.1 Types of Equity

The goal for any type of equity or social justice policy is to provide a just and efficient solution to the overall population that does not impair people negatively. The Stanford Encyclopedia of Philosophy describes equality as having two main parts, one which is descriptive and is concerned with how different groups are defined and another which is normative, focusing on legal terms or definitions that define how and what equality is. Because of the lack of guidelines on what this threshold of the negative effects of a policy entails, this is usually left up to the modeler. This means that the type of equity selected will result in different outcomes regarding whether a project provides successful improvements with regards to equity and environmental justice.

Whether something is fair or equitable can be debated and these terms are used in place of each other frequently making it harder to distinguish between the two. The World Health Administration gives a definition of equity saying that, “The absence of avoidable or remediable differences among groups of people, whether those groups are defined socially, economically, demographically, or geographically.” (Davis and Pilkington, 2019). This definition lays down a foundation for things that must be considered in transportation policy, specifically dealing with the terms avoidable and remediable. Accessibility is important when dealing with social equity in transportation regarding essential services such as education and healthcare. While there may be an opportunity to have discussions with land use planners to make these more available to all areas of the population, it would be impossible to devise a system that allows everyone to experience the same travel time to these services. Nonetheless, the equity types chosen will affect the model’s results. Their differences are discussed below:

Horizontal equity seeks to treat individuals that are classified in the same group in similar manners. This classification is down to the modeler and can be based on geography, demographics, income, etc. The main goal of this type of equity is that the benefits and impacts to each of the groups is the same. In transportation, this would entail similar benefits or impacts in congestion improvement, net emissions, noise, or safety.

Vertical Equity is concerned with minimizing the gap between disadvantaged populations. In this case, the populations worse off at the time of the analysis are treated as protected populations and prioritized. This differs from the previous type of equity where the benefits and impacts amongst groups were the same. With vertical equity, these effects may be distributed unevenly as long as the gap between protected and unprotected groups is minimized.

Territorial equity deals with geographic classification of groups and takes ideas from both vertical and horizontal equity. Regions defined as homogenous (with similar demographics and income) should receive similar amounts of funding for transportation. On the other hand, regions that are lagging in terms of accessibility or public funding should receive more funding and support to minimize the gaps in accessibility and services that they may be experiencing.

Egalitarianism is like the idea of horizontal equity, but instead of treating like individuals equally, this theory seeks to treat all groups in the same way. This disregards differences in social and economic classes as well as any other means that could be used to classify individuals. Given that the goal is for all to be treated equally, egalitarian policies also seek to reduce differences between people, therefore if any were to exist. This is done at the expense of the system, meaning that reducing the impact on protected groups is put above the overall benefit of all.

In addition to these types of equity, there are several other ideas that can form policies and shape the objectives that transportation projects seek to attain. Some policies will seek to maintain what is called a level-playing field (van Wee, Mouter, 2019) which essentially boils down to having the same amount of funding for infrastructure and taxation on different transportation sectors. Another idea that could guide how to achieve equity is with compensation for the groups or individuals that are most impacted by new transportation policies. This could entail loss of accessibility, increased contamination, more noise pollution or any other negative effect stemming from a new project. Although this could be seen as a short-term solution, with those negatively affected receiving some form of benefits, it risks exacerbating existing gaps in inequality between groups. Conversely, in certain cases it is an appropriate policy to implement. Such is the case in the London cordon toll, where residents of the zone within the toll, who must make more trips in and out of the zone, get a 90% discount on the toll itself. Two more aspects can also guide the implementation of these policies: spatial equity and social equity. The former refers to the location of a group or individual and how infrastructure or transport policy affects them. The latter considers the personal or economic impact on a certain group due to the changes to the system.

2.2 Social Equity Theories

The types of equity will define how social classes can be defined and what parts of the population will be classified as protected or unprotected. Transportation planners will also use these types of equity to guide the model's objectives with a guiding social equity theory. A social equity theory will serve as a justification of the model’s results, the impacts to the system (both positive and negative), the allocation of resources, and the decisions made by policymakers and engineers in charge of these projects. The distinctions between these will affect these matters and are discussed below.

Utilitarianism is a principle focusing on the benefits of society**.** In short, it seeks to maximize the utility for the whole system. In transportation, this could, for example, result in minimizing the TSTT for the system, implementing policies or making changes in infrastructure that move the system towards a system optimal state. If the aim of the intended changes does not deal with travel time or cost, it would center on maximizing the benefits for the whole system in the desired metric, which could also include emissions, noise, etc. A drawback of this theory is that by maximizing the utilities for the system, some groups or individuals may be neglected leading to a policy or project that furthers the existing inequality despite providing benefits for the system.

Egalitarianism is also considered a social equity theory. Just as it was defined above, the aim is to reduce inequalities that exist in society. Doing this will result in all members of a community receiving equal benefits and bearing the same impacts. In contrast with utilitarianism, reducing the gap between groups is given more importance than maximizing the benefits to society. With transportation policy, an application of this theory would be the redistribution of wealth, through taxpayer money, to reduce inequality between income groups. Ultimately, this theory's goal is to ensure that all members of society are treated equally.

Socialism is dependent on the application, with different definitions used in economics and political science. Regarding transportation issues, the aim of socialism is to create an even share of the benefits and impacts of the policy amongst society. Although this may seem similar to egalitarianism, it differs in that it the egalitarian theory does not take social classes into account during the decision-making process.

Rawl’s Theory of Justice takes elements of egalitarianism but adds certain constraints to the policy. Once again, the aim is to treat all groups within society equally (Rawls, 2009). The caveat is that there can be uneven distributions of benefits if this reduces the inequality between groups. The benefits for lower income groups must be progressive when looking at the impact on society (France-Mensah et al., 2019). Progressive policies lead to a positive longer-term impact on disadvantaged groups. While a regressive policy has mostly negative effects on these protected populations. (Litman, 2016). This theory also looks at a minimum threshold for the benefits that can be obtained by different groups in society and could be considered a theory that is a mixture of vertical and horizontal equity (France-Mensah et al. 2019).

Deciding the correct theory to guide the implementation of the policy makes a difference in the analysis, the consequences of the decisions, and the long-term impact on society for different groups. Therefore, since no guidance is provided by the authorities, when including equity in the scope of a transportation project it is important to find a social equity theory and type of equity that guides and justifies the decisions made during these projects.[1] [1]

2.3 Data Issues and Needs

Transportation planners face three different challenges when integrating social justice into policy: data collection, the definition of equity, and the use of appropriate units of analysis

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[1] For a detailed description on how these social equity theories vary in their formulation the reader should look at: Integrating social equity in highway maintenance and rehabilitation programming: A quantitative approach by France-Mensah et. Al (2019) and A conceptual framework to formulate transportation network design considering social equity criteria by Behabani et al. (2019). These two papers provide mathematical formulations for each social justice theory discussed, something that is necessary to implement them in projects and planning.

(Duthie et al., 2007). This section will focus on the issues that arise during data collection which are common in transportation projects.

When incorporating equity into a project, most modelers or planners will split parts of the network into groups. This can be done demographically, racially, socially, by income, etc. But how these groups are defined is important because it will create boundaries between what is deemed inequitable and what is not. Therefore, the main issues with data collection deal with having current data in terms of race and income, which are some of the main methods that are used to classify groups. This is not always available and will vary by country. According to the United States Census Bureau, a census is performed every 10 years, meaning that projects that are worked on during this gap may have unreliable or outdated data that does not reflect the current state of the city or region that will be affected. At this point, a decision must be made on how to best estimate the data based on growth during past decades and recent growth within the region. Simple imputation of missing values or replacement by the average income in an area will not suffice as these will not be able to predict future changes in the development of cities and regions. This will be unreliable as recent developments may cause large numbers of people to move in or out of a region creating lots of uncertainty regarding the data and the spatial distribution of race and income.

Another important aspect of data collection is the spatial distribution of trip ends (Duthie et al., 2007). Without these it is not possible to create accurate trip tables reflecting the current state of the system. Duthie suggests communication between municipalities and land developers as this would allow municipalities and the companies working with them to have a better idea of where new large developments would be placed and consequently providing better estimates of what trips will be made by different groups depending on their geographic location and the location of the new land developments. Overall, improvements in the accuracy of data collection, communication between large agencies and land developers, as well as the implementation of accurate tools to estimate changes in population in between years when accurate census data is not available will make for more accurate groupings and classifications of people, which in turn will lead to better results in equity analyses.

2.4 Units of Analysis and Guidelines

The unit of analysis implemented by the modeler will certainly have effects on the results of the study. These can range from individual, groups, or geographic units. Methods such as traffic survey zones will not be effective (Duthie et al., 2007). Similar to the effect of gerrymandering, traffic survey zones can be redefined inconsistently with areas belonging to one zone and later belonging to another, which leads to issues in defining who the protected populations should be. Common metrics to decide how equitable a measure is are the Gini Index and the Theil Index.

The Gini Index looks at the level of inequality as a distribution and expresses it graphically. The units for the analysis are placed on the X-axis based of on the variable for which the distribution is shown. The Y-axis deals with the income of the distribution, showing the cumulative distribution of income for the region or area of study. The 45-degree line across the graph is called the Line of Equality and the curve below it is called the Lorenz curve, which represents the distribution of income or the chosen X variable for the specified group. The unit that is used in the X-axis can vary and could be related to accessibility, contamination, safety and other measures (van Wee, Mouter, 2021).

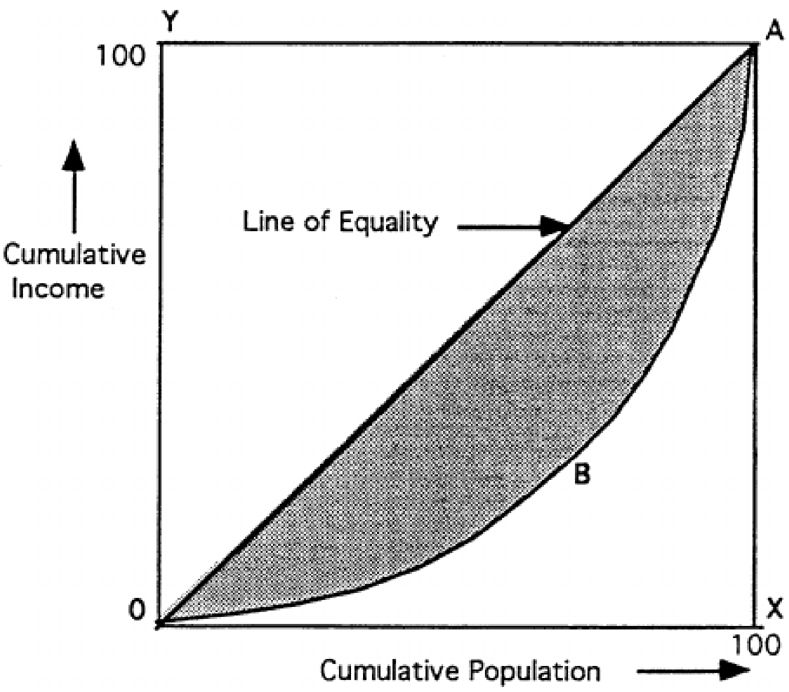

Figure 1: Gini Index curve, where the Gini coefficient is measured as the quotient of the shaded area over the area below the line of equality. (Pandey, 1996)

In equity discussions it would be appropriate to use it for different areas to see what the current Gini Index of the area is based on the existing state of the system and then this could be compared to the Gini Index once the changes are made to measure the change in the inequality of the system. One advantage of using the Gini index is that it is easy to depict graphically, making it easier to convey how the inequality in a region is changing.

Another measure that is used is the Theil Index, which just like the Gini Index also measures inequality. According to the United States Census Bureau, “The Theil Index measures an entropic distance the population is away from the ideal egalitarian state of everyone having the same income.” The idea is to achieve maximum entropy which would lead to the most equal state. The Theil Index is measured in negative entropy; therefore, a higher number would demonstrate lower entropy and a more unequal state. A lower number, on the other hand, would correspond to a more equal state.

$$T = \sum_{p=1}^{n} \left\{ \left(\frac{1}{n}\right) * \left(\frac{y_p}{\mu_y}\right) * \ln\left(\frac{y_p}{\mu_y}\right) \right\}$$

Figure 1:Theil statistic equation, where n is the population number, p is the index of an individual in the population, y_p is the income of the person p, and µy is the average income of the population.

The reason for the use of negative entropy is that this allows the Theil Index to represent inequality. Similarly to the Gini Index it could also be used to show the effects on inequality on a certain area due to a transportation project. Figure 2 shows the Theis statistic equation. The lowest value that can be achieved by the Theil statistic will occur when the income amongst all individuals in the population is the same, in which case the value will be 0. If, at the other extreme, one person holds all the income then the maximum value of the Theil statistic will occur at ln n. These values represent maximum equality and inequality, respectively. The Theil index involves a more complicated process to calculate and is usually displayed graphically over a certain time period. Unlike the Gini index, there is no graphical display that shows perfect equality and this, coupled with the more complex equation, could make it harder to convey the Theil Index’s meaning. (van Wee and Mouter, 2021)

Another option that could be pursued is to use a proprietary metric. This could be done by formulating the problem as an optimization problem, which would usually be done in accordance with the social equity theory guiding the policy. A method of this type can be advantageous because if solved properly it could result in an optimal solution for the problem to be solved and can give more insights on how the changes to the network are affecting specific origin-destination pairs and groups within the network. For example, in a 2008 study by Duthie and Waller they formulated an equity-centric method for the network design problem, by presenting eight options that took into account equity with regards to different transportation metrics such as congestion and travel time. Their formulations classified the overall population of the network into protected and unprotected groups, allowing for as many unprotected groups as desired. They accounted for changes in the network that would be beneficial such as capacity increase or tolling and minimized the transportation metric. A couple of these formulations considered equity by including the difference between the network before and after the proposed changes. By proposing their own method, they were able to attain results that were more relevant to the problem they were solving. Although this yields better problem-specific metrics, because they are not widely used a drawback can be that these metrics can be hard to communicate to the general public.

There are other measures of data that could be used to define changes in inequality and improvements due to projects, such as the interquartile range or the use of percentiles. Looking at variations in these measures before and after a project is implemented could suggest that there is a positive or negative effect to the changes made. Because these measures are still numerical, the modeler could still see quantifiable changes in the population due to the effects of the project. The downside of using these measures is that they do not focus specifically on measuring inequality and as a result they do not provide the same level of detail as the former two methods do.

Consequently, the most used methods to incorporate equity and social justice into transportation analysis are the Theil and Gini Index. A study by van Wee and Mouter in 2021 performed a search to find which metrics were the most common in transportation studies and projects. They looked at literature, filtering it using key words such as equity, fairness and accessibility. They found that at publication 7 of the 10 most recent papers focused used the Gini Index as a measure, regardless of the type of social equity theory used. Furthermore, they expanded their search to include the names of several measures in their key words, finding that the Gini Index was used by the majority of researchers. The Theil Index was the second most used measure, although it was a distant second to the Gini Index. These findings suggest two things: it is easier to convey changes in equity using equity specific measures and that the choice of measure will affect the results. Therefore, it is important that the modeler make an informed decision on what metric to use based on the topic and scope of the study.

The guidelines regarding how to integrate social equity into studies vary by country and are not clearly defined, but efforts have been made to include these policies in all types of projects, including transportation. The Intermodal Surface Transporation Equity Act in 1991 began to take equity into account in transportation policy in the United States (Karner and Niemeier, 2013). Following this, there was an enforcement of environmental justice in all federal agencies by President Clinton’s 1994 Executive Order 12898, which stated that federal agencies should include equity in their guidelines and consider lower income groups as populations that needed to be protected. Following this order, the Federal Highway Administration (FHWA), Federal Transit Administration (FTA), and United States Department of Transportation (DOT) released advice following the executive order. In 1997, the DOT released the proposed and Final Environmental Justice Orders, while in 2007 and 2012 the FTA proposed guidance following the executive orders that sought to include lower income groups and minorities in the planning process and analysis methods. Despite these advances, there is still no concrete guidance, and many have asked for a better description of what including these groups in the analysis entails. (Karner and Niemeier, 2013)

2.5 Citizens Perspective on Congestion Pricing

Depending on the country, the general population's perspective on congestion pricing can have a significant effect on the success of its implementation, as well as if it becomes implemented. In countries where the government has a stronger influence, it is easier to implement these policies without overwhelming approval, however this is not the case all over the world. Tolling and congestion pricing can sometimes generate negative reactions amongst citizens as there is a prevailing thought that it is most beneficial for the wealthy and that lower income communities must pay disproportionate amounts compared to their income. These concerns are valid and are the main reason why equity should be considered when implementing a congestion pricing scheme. A policy that does not take into account the impacts to all communities will not be widely accepted, and even if it results in overall benefits for the system, could end up making the inequality within the area worse. Furthermore, many countries where these schemes could be beneficial require citizens to vote on the approval of these systems, so a comprehensive analysis is needed to receive positive feedback and get the policy implemented.

This section will review a couple of studies aimed at tackling the general population's feeling towards proposed and existing schemes. Through surveys and analysis of the changes to the system, it is possible to gauge how efficient these policies have been for the system and if they have been equitable at the same time, while also evaluating the feeling towards these changes.

Generally, to state that congestion pricing is unfair would require looking at how schemes affect lower income groups, regarding the amount they pay (total and relative to their income), and how the benefits and impacts are distributed. There are two main perspectives that evaluate how congestion pricing is viewed: the consumer perspective and the citizen perspective. (Nyborg, 2000). The consumer perspective is focused on how someone is affected by the toll, so how much they pay, what the benefits are in terms of travel time, and what their specified value of travel time is. The citizen perspective is subjective and defines what someone values as a fair policy from the whole system's point of view without considering the effects the policy may have on them personally. (Eliasson, 2014). If someone were to be completely unbiased then there would be no relation between these two perspectives, but it is most likely that someone that is incurring high costs will feel like the policy is unfair globally. It's also harder for people to make these decisions without concrete data showing what the effects of the policy are.

A study was conducted by Eliasson in 2013 where four surveys were sent out to citizens of Stockholm, Helsinki, Lyon, and Gothenburg. Two of these cities, Gothenburg and Stockholm, have implemented congestion pricing schemes. Lyon and Helsinki have not, but their have been plans to implement them. Therefore, the study was able to gauge citizens' opinions towards these plans before and after they have been implemented, by asking what their vote would be in a referendum in favor of congestion charges.

To give more context on what the citizens were voting on, the proposed and existing schemes are described. The Stockholm toll is a cordon toll that goes around the city center with users paying €1 to €2 on workdays between the hours of 6:30 A.M. and 6:30 P.M. The Gothenburg system is similar. It is also a cordon toll around downtown with users paying for passage in or out of the cordon during workdays. The charge for these tolls is from €0.8 to €1.8. The system that was proposed in Helsinki, was based on GPS on vehicles. Tolls would be paid on a per kilometer basis within the city center and in a second cordon-like area that encompasses the remaining part of the city. Finally, the proposed Lyon toll would force drivers to pay €3 when entering the downtown area, without any time or day of the week stipulations. It’s also important to note that this would be a daily charge, instead of a charge per trip like in the Swedish systems. This scheme would cap payments at €50 monthly per user.

Eliasson found that higher earners were paying more on average than lower earners in all four cities in terms of total payments made. But when this value was normalized by the income of each group, lower income groups were paying a greater amount of their income in all four cities. This would suggest that people would suggest that people would be justified to say that these systems are promoting inequity to some extent but the purpose of the congestion pricing scheme has to be considered in this as well. Many of these projects seek to collect revenue for infrastructure projects for the cities and surrounding areas, therefore a fair assessment of the equitable benefits of the project would also include what positive impacts to the system come as a result of these schemes.

Survey results showed support was correlated with the toll users would have to pay. As this price rose, so did the negative responses towards the existing and proposed plans. The greatest decrease in support was seen from users who went from paying no toll to having to pay a monthly toll amount each month. These results would support the idea that the users that are most opposed to these schemes are those who pay the least amount, which would make sense as it becomes a new expense that they have to budget for.

The surveys sent out for Gothenburg were distributed in two batches. One in 2012, before the scheme's implementation and the second in 2013, after it was implemented. This meant that the results before and after the implementation could be compared, unlike in any of the other cities. Eliasson’s results showed that support increased among all income groups after the toll was put in place. This would suggest that the biggest barrier towards getting congestion pricing scheme to be approved by the public is the initial step, after this people become accustomed to it and budget for it within their incomes, and if the project is providing its intended benefits acceptance will tend to be higher than before it was implemented. This result has also been observed in HOT lanes in the United States (Finkleman et al.,2011) where the authors found that support also increased once the HOT lanes had been put in place.

In addition to gauging the public perception of congestion pricing and tolling schemes to evaluate their feasibility it is also important to include citizen feedback and inputs throughout the process to ensure that the scheme is accepted and that it provides equitable benefits to its users. In this upcoming year, New York City will be implementing a congestion pricing scheme that will charge users entering certain parts of Manhattan. As is well known, congestion in New York City is amongst the worst in the world, causing losses of time that affect people, businesses, and essential services. The Metropolitan Transit Agency (MTA) of New York says that this project is, “an opportunity for New York to address climate change, improve public health, and boost the economy... And for the vast majority of people who enter the CBD by subway, train, or bus congestion pricing will mean better transit service and faster commutes.” The goals of the MTA are clear, but for a project that will affect the lives of so many people it is important that citizen feedback is provided. As such, public hearings have been held and comments have been accepted to discuss potential issues with the toll, toll charges, and general questions about the system. This type of communication, changes people’s perspective on projects congestion pricing schemes and tolling towards a more positive outlook.

As can be seen several factors come into play in the inclusion of equity in transport policy. Distinguishing a type of equity and social equity theory to follow the project can guide the project on decisions regarding benefits, impacts, allocation of resources and more. Deciding upon the appropriate metric to use is important because different metrics will result in different measures of inequality.

Chapter 3: Cordon Toll Simulation

To evaluate the effects that congestion pricing has on network users, ten cordon tolls were simulated on the Sioux Falls network. These tolls were placed in different areas around the cordon to evaluate how this would affect lower-income groups and the system overall. Comparisons were made between travel time and costs before and after the implementation of the tolls. Following a similar framework to that proposed by Behbahani et. al (2019), a specific type of equity and social equity theory guided what outcomes were considered effective in terms of equity.

3.1 Equity Theory Considerations

As mentioned previously, the choice of a specific type of equity and social equity theory are important in the decision-making process, the justification of attributes, and the resource allocation in planning projects.

For this thesis the objective was to consider a type of equity that would result in benefits specific to lower income groups, by decreasing the gap in travel time, and if possible, cost, to these users. As such, and according to the types of equity defined above, the best option would be vertical equity because the benefits to all social classes would not be equal, there would be populations that would be considered protected populations, and the overall winners of the scheme would be the protected population, meaning that they would receive a larger share of the benefits.

With regards to the social equity theory that guides what results are acceptable and how to allocate resources, it is necessary for it to align with key principles of horizontal equity. Such as, decreasing the gap in equity and allowing for an uneven distribution of equity to achieve this goal. Utilitarianism would not fit this model as it seeks to maximize the benefits of the system and that would not be considered equitable for the previously defined purposes. Egalitarianism's end goal of having all members of society achieve the same benefits would be considered adequate, but before reaching this state the gap between groups needs to be narrowed. Therefore, the best option is Rawl's Theory of Justice, which seeks to treat all groups equally, except for protected groups, which can be prioritized. This would justify the creation of these groups and heightened importance given to the benefits that a toll has on them specifically. Therefore, following these theories, a cordon toll will be considered to be equitable if it reduces travel time to the protected population and the specific low-income nodes, even if TSTT for the system is not reduced overall. If reductions in travel time are not equal amongst group, then an equitable toll will provide more benefits to the protected population.

3.2 Group Classification

Protected and unprotected groups for the network simulation were based on income distribution. The Sioux Falls network has 24 nodes, which are usually represented as shown in Figure 2. This representation is useful for network modeling problems but does not depict the geographical location of the nodes. To classify each node as part of a lower-income or high-income area the geographic location of each node was found using the node coordinates provided by Ben Stabler's Transporation Networks Sioux Falls file: (https://github.com/bstabler/TransportationNetworks/tree/master/SiouxFalls).

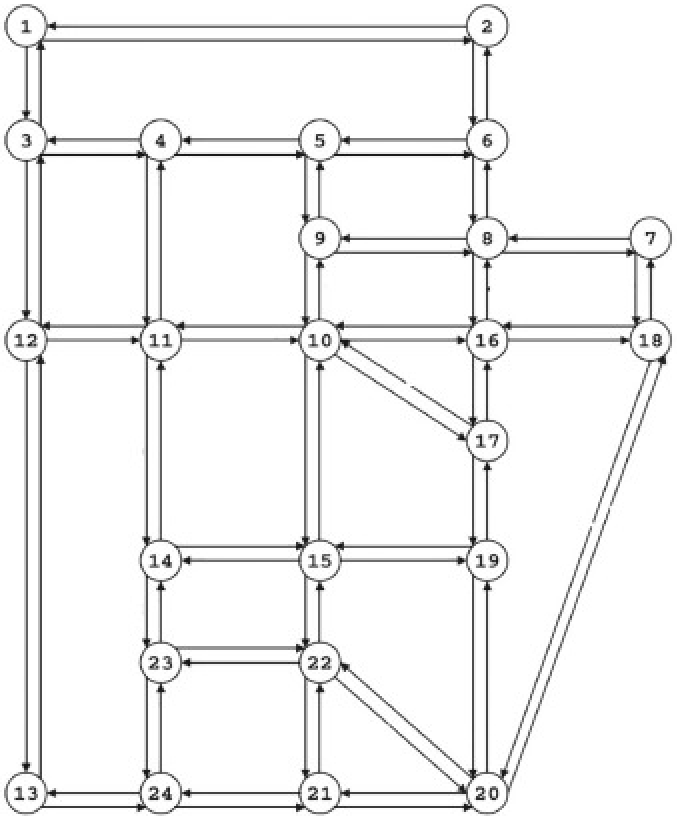

Figure 2: Network representation of Sioux Falls network and geographic location of nodes on a map

Once the location of the nodes was found, household income distributions from the United States Census Bureau was used to classify the nodes. Each node belongs to an area with a different median household income distribution. Nodes located at the border between two areas were assigned to the area with less nodes within it, to ensure that individuals living in those areas were also represented in the analysis.

The median household income for the areas within the city ranged from $44,000 to $104,000 annually. Table 2 shows the median household income for each of the nodes. Thirteen of the twenty-four nodes had a median household income between $43,000 and $46,000, so it was easy to classify these as the protected class or low income group. The remaining nodes were classified as the unprotected class or high income group, despite the wide range of household incomes. This does affect the accuracy of the model because the value of travel time for this group will come from the average of the median household salaries of all these nodes. Realistically, most nodes belonging to this class experience a higher or lower value of travel time, but this approximation was made because only two classes are being used. Even in larger networks, approximations like this must be made if people are separated into classes, because it is not reasonable to have a class for each node or even just a handful of nodes, when a network has hundreds or thousands of nodes.

Table 2: Median Household Income in Area Corresponding to Node

Node	Median Income	Node	Median Income	Node	Median Income	Node	Median Income
1	$61,000	7	$46,000	13	$86,000	19	$96,000
2	$46,000	8	$46,000	14	$66,000	20	$105,000
3	$45,000	9	$46,000	15	$96,000	21	$105,000
4	$45,000	10	$46,000	16	$43,000	22	$105,000
5	$45,000	11	$46,000	17	$43,000	23	$70,000
6	$46,000	12	$60,000	18	$44,000	24	$105,000

3.3 Simulation Procedure

The simulation compares the effects of the cordon toll on the network at user equilibrium state. Under these conditions it is assumed that users of the network select the route that will minimize their travel time with exact knowledge of the network conditions. These assumptions are reasonable. When selecting a route to a certain location most individuals act selfishly, meaning that they do not consider how their choices will affect others' travel time. The second assumption is also justifiable, people making daily commutes know which routes experience greater levels of congestion because they make these trips regularly. The principle of user equilibrium results in a network state where all used paths between the same origin and destination have equal and minimal travel time. To achieve this state the traffic assignment problem must be solved. The traffic assignment problem is formulated according to Beckmann et al. (1956):

$$\min_{\boldsymbol{x},\boldsymbol{h}} \sum_{(i,j)\epsilon A} \int_0^{x_{ij}} t_{ij}(x_{ij})dx$$

$$s.t \quad x_{ij} = \sum_{\pi\epsilon\Pi} h^{\pi}\delta_{ij}^{\pi} \qquad \forall(i,j)\ \epsilon\ A$$

$$\sum_{\pi\epsilon\Pi^{rs}} h^{\pi} = d^{rs} \quad \forall(r,s)\ \epsilon\ Z^2$$

$$h^{\pi} \geq 0 \qquad \forall\ \pi\ \epsilon\ \Pi$$

Figure 3: Beckmann’s formulation for the traffic assignment problem

Where:

$t_{ij}(x_{ij})$ = travel time on a link as a function of flow on the link

In this formulation the travel time as a function of the flow on the links is minimized. The first constraint ensures that link flows are compatible with path flows, basically ensuring that all the flow is accounted for. The second constraint makes sure that the path chosen is a feasible path from r to s. The final constraint maintains the nonnegativity of the path flows. (Boyles et al., 2021). The problem is solved using the TAP-B code from the SPARTA Lab at the University of Texas at Austin, which is an implementation of Dial’s Algorithm B, a bush-based algorithm for solving traffic assignment. Algorithms like Dial’s Algorithm B are a type of path-based algorithm that uses bushes, which are acyclic subnetworks where all nodes can be reached from the origin or root of the bush.

The base-case of the problem will solve for the static UE of the Sioux Falls network with no tolls on the users. To evaluate the effect of the cordon toll on the network, links going into the cordon are tolled. This requires a small modification to the travel time function that is minimized in the objective function of the traffic assignment function. The function commonly used to calculate travel time on each link is the Bureau of Public Roads (BPR) function.

$$t_{ij}(x_{ij}) = t_{ij}^{0} * \left(1 + \alpha \left(\frac{x_{ij}}{u_{ij}}\right)^{\beta}\right)$$

Figure 4: Bureau of Public Roads function describing travel time as a function of flow on a link (Gore et al., 2023)

Where:
t_{ij}^{0}= travel time at free flow speed
u_{ij}= capacity on the link
α = model parameter, usually 0.15
β = model parameter, usually 4

To account for the tolling of the links, a toll factor which is based on an approximation of the value of travel time for each driver is added to the function.

$$t_{ij}(x_{ij}) = t_{ij}^{0} * \left(1 + \alpha \left(\frac{x_{ij}}{u_{ij}}\right)^{\beta}\right) + toll * \tau$$

Figure 5: BPR function with toll factor and toll on link considered

Here τ is the toll factor, attempts to capture the value of travel time for drivers on that link. In this case it is the inverse of the salary of drivers on the link. This salary is in units of $/.01hr because the Sioux Falls network uses these units for free flow travel time. When multiplied times the toll charge, the units become units of time and can be added to the rest of the

BPR function. The use of the yearly salary to establish how much drivers value their time will result in higher values of travel time for lower income drivers and the opposite for higher income drivers. Higher earners usually have more flexibility in their jobs, with hybrid or remote work options, and the ability to spend more time on leisure trips therefore they may not value their travel time as much as lower earners who work fixed schedules and need to be at work at specific times, making this assumption reasonable.

When solving for the UE with the TAP-B software, the values achieved will be TSTT when the network is untolled and total system cost (TSC) when the network is tolled. Both have units of $travel\ time * flow$, which in the network used results in $.01hr * vph$. Without tolls the value that results from solving just reflects the travel time of the system for all drivers. Once tolls are added to the BPR function the output provided by TAP-B is no longer just travel time, but a reflection of traveler's cost, which is why it was given this name.

For the single class and multi-class simulation the links that are directly entering the cordon are tolled based on this toll factor. For single class, the salary used as a value of travel time was $50,000/yr. which was the lower end of the 50th percentile of household incomes in the city, resulting in a toll factor of 4.16 .01hr/$. In the multi-class simulation, the toll factor was based on the incomes attributed to each group. For the lower income group, the median income was $44,000/yr. which results in a toll factor of 4.62 .01hr/$, while for the high-income group the median income was $77,714/yr. resulting in a toll factor of 2.68 .01hr/$. Users entering the cordon through a link whose head node was a low income node were tolled with the low-income toll factor and the same procedure was applied for users entering the cordon through links whose head node was a high income node.

3.4 Demand Adjustments

In the multi-class portion of the simulation the whole network's demand stayed the same, but it was split into two different groups, meaning that the total demand sum of both groups should be equal to the demand in the single class simulation. With nodes already classified into lower income and higher income groups geographically, it was assumed that trips that originated at low-income nodes would have a higher percentage of users belonging to this class because each node is within an area of similar income. The same logic was applied to higher income nodes.

The salaries used to assign nodes to each group were the median value for income in each area. This would imply that about half of the trips originating from these nodes would belong to that class. To determine how to assign the remaining 50% of trips originating from nodes belonging to different classes the income distribution of Sioux Falls was used.

Table 2: Income distribution for city of Sioux Falls (U.S. Census Bureau, 2022)

Income	Percentage	Cumulative
Less than $10,000	6%	6%
$10,000 to $14,999	2.60%	8.600%
$15,000 to $19,999	1.30%	9.900%
$20,000 to $24,999	2.50%	12.400%
$25,000 to $29,999	3.60%	16.000%
$30,000 to $34,999	4.70%	20.700%
$35,000 to $39,999	3.60%	24.300%
$40,000 to $44,999	5.10%	29.400%
$45,000 to $49,999	3.30%	32.700%
$50,000 to $59,999	9.50%	42.200%
$60,000 to $74,999	11.10%	53.300%
$75,000 to $99,999	12.30%	65.600%
$100,000 to $124,999	11.40%	77.000%
$125,000 to $149,999	7.10%	84.100%
$150,000 to $199,999	8.50%	92.600%
$200,000 or more	7.40%	100.000%

The value of time for the lower income group was based on a salary of $44,000/yr. and for the higher income group it was $77,714/yr. Therefore from the table, about 29.4% of households in Sioux Falls made less than the income of the lower income group and 46.7% of households in Sioux Falls made more than the income of the higher income group. To account for the fact that both high- and low-income areas would have more residents belonging to each group than just those at the median the following formulas were used to distribute trips.

$$High\ Income\ Trips\ from\ High\ Income\ Nodes = 0.5 + 0.5 \ast .467 = .734$$

$$High\ Income\ Trips\ from\ Low\ Income\ Nodes = 1 - .734 = .266$$

$$Low\ Income\ Trips\ from\ Low\ Income\ Nodes = 0.5 + 0.5 \ast 294 = .647$$

$$Low\ Income\ Trips\ from\ High\ Income\ Nodes = 1 - \ .647 = \ .353$$

The 0.5 factor multiplied by the percentage of remaining trips higher than the average salary values for each class was chosen arbitrarily to weight the amount of trips that would be below or above the thresholds for the corresponding class. Below is an example of how trips were distributed for nodes 1 and 2, for both high and low income trips. Node 1 is a high income node and node 2 is a low income node.

Table 3: Sample Demand Adjustments for High and Low Income Trips

Demand Adjustments for High and Low Income Trips			Destination Node
			3
Origin Node	Original Trips	1	100
		2	100
	High Income Trips	1	73.35
		2	35.3
	Low Income Trips	1	26.65
		2	64.7

From the table it can be seen that the low and high income trips add up to the value of the original trips to and from a certain destination. This ensures that the total demand for the network is the same while distributing a proportion of trips to each class, based on how many people in Sioux Falls fall within the high or low income thresholds that separate the classes.

Chapter 4: Results

The results of the implementation of the ten cordon toll son the network are presented in the following chapter. First, the single class results will be presented, followed by the multi-class and a discussion of the differences that were noted between the two. Due to the small size of the network, it was possible to perform a link by link analysis for each cordon toll, at each toll value, giving more insight into what was happening at specific links.

4.1 Single Class Results

The addition of a cordon toll to the network yielded different results across the board, but a few trends emerged. The addition of the toll yielded higher values of Total System Cost (TSC) for all cordons at all toll values charged, but individual links had changes in travel time and flow. In general, the higher the toll value imposed on the users, the more links were affected across the network. For the most part, charging users entering the cordon with a $1 toll yielded small improvements in TSTT. As the toll increased, the value of TSTT when compared to the no-toll case increased but it did so differently depending on the cordon that was applied, with some cordons having steady increases in TSTT and cost with each new toll increment, while others had sharp spikes after the introduction of a certain toll value. The effects of the cordon were mostly beneficial to links that were made up the cordon or were geographically close to the nodes that formed the cordon. The following will overview the results of the best and worst performing tolls in terms of system-wide TSTT change as well as analyzing how travel times and flows changed at the link level.

The first cordon toll implemented (CT1) showed the best improvements in TSTT for the $1 charge and was the only toll that had an decrease of TSTT when a $2 toll was applied to users of the system. TSC values were similar to the values obtained for other cordons placed around the city, but when users where charged higher tolls, $8 and $16, the TSC spiked and resulted in the second highest TSC value cost at these tolls amongst all the tolls.

Table 4: TSTT and TSC for Cordon Toll 1

Sioux Falls (Cordon Toll 1)					
Toll Factor (.01hr/$)	**Toll ($)**	**TSTT(.01hr*vph))**	**TSC(.01hr*vph)**	**Delta(.01hr*vph)**	**Cost Due to Tolls (.01hr*vph)**
0	0	7,479,916.43	7,479,916.43	-	-
4.16	1	7,438,874.34	7,827,168.10	(41,042.09)	388,293.77
4.16	2	7,442,701.12	8,217,285.27	(37,215.31)	774,584.15
4.16	4	7,544,486.31	9,050,406.32	64,569.88	1,505,920.00
4.16	8	7,942,646.88	10,802,763.96	462,730.45	2,860,117.08
4.16	16	8,301,929.23	13,859,689.17	822,012.80	5,557,759.94

The cordon is placed around nodes: 10, 11, 14, 15, 22, 23, which is placed around a combination of lower income and higher income nodes. To evaluate whether significant effects to each link's flow and travel time were caused by the toll the average flow and travel time value for the base case was calculated, 10% of these average values was defined as the required value for change to be significant on a link, in terms of travel time or flow. These values were 0.088 .01hr for travel time and 115.47 vehicles for flow. For this cordon toll, the amount of links affected and the average effect on these links in terms of flow and travel time is summarized in the table below. Where the left column is change link flow and the right column is change in link travel time.

Table 5: Effect of CT1 on Link Flow and Travel Time

$1 Toll		
	Flow (vph)	Time (.01hr)
Average Increase	458.753484	0.8770922
Average Decrease	-534.23039	-0.463584
Count Increase	31	16
Count Decrease	22	30

An in-depth look at the effect on the links. Links that started at one of the nodes that formed the cordon had significant decreases in travel time, but not all these links had significant decreases in flow. Most of the negative effects created by these tolls were on links that began at nodes 6, 7, and 8. These links not only saw an increase in travel time, but also saw much higher flows than in the base case. Thus, although there were positive effects on nodes in the lower income group and overall TSTT for the system went down, this was only for the nodes that made up the cordon. Throughout the rest of network, the links that saw the most negative effects belonged to the lower income group.

Cordon Toll 5 (CT5) formed a cordon connecting nodes 5, 6, 8, 9, 10, and 16, all of these nodes belonging to the lower income class and located in northeast side of the city. It was the cordon toll that exhibited the worse performance in terms of change in TSTT compared to the base case.

Table 6: TSTT and TSC for Cordon Toll 5

Sioux Falls (Cordon Toll)					
Toll Factor (.01hr/$)	**Toll($)**	**TSTT(.01hr*vph))**	**TSC(.01hr*vph))**	**Delta(.01hr*vph)**	**Cost Due to Tolls (.01hr*vph)**
0	0	7,480,152.30	7,480,152.30	-	-
4.16	1	7,581,277.32	8,031,549.05	101,360.89	450,271.73
4.16	2	7,701,972.66	8,580,371.97	222,056.23	878,399.31
4.16	4	8,030,086.51	9,697,788.25	550,170.08	1,667,701.73
4.16	8	8,979,013.82	12,032,311.92	1,499,097.39	3,053,298.10
4.16	16	10,156,122.46	15,931,565.51	2,676,206.03	5,775,443.05

Compared to CT1 the increase in time is much greater for CT5, with a time delta that approximately doubles every time that the toll is doubled. Despite the negative effects on travel time, the cost due to tolls is comparable to that of CT1, meaning that the effect of the tolls on the travel cost was similar for both tolls despite one outperforming the other in terms of travel time. On a system basis, CT1 would still be chosen over CT5 because it provides TSTT savings at lower charges and a lower Total System Cost, but it is surprising that the cost due to tolls is so similar for both cordons.

On a link level the performance of CT5 was the opposite of CT1. For the $1 toll, a similar number of links showed significant change in flow and travel time, but the trends were reversed. More links experienced a positive impact in terms of flow. Out of the links that saw changes in travel time, most of these links saw increases in travel time.

Table 7: Effect of CT5 on Link Flow and Travel Time

$1 Toll		
	Flow (vph)	Time (.01hr)
Average Increase	298.507437	0.7869745
Average Decrease	-415.5331	-0.553763
Count Increase	26	28
Count Decrease	30	16

The average overall changes in travel time were more significant than CT1, with a lower average increase in travel time and a higher average decrease in travel time. In fact, the average decrease in flow was the only measure where CT5 was outperformed by CT1, which is surprising given that CT5 increased TSTT much more than CT1.

As with most of the cordons, the links that showed constant decrease in travel time where those that originated from one of the nodes that made up the cordon. This is beneficial in terms of equity, because all of these nodes are part of the lower income class. Most importantly, the effects on the rest of the network where also beneficial for the lower income class. A few links originating at a node belonging to the protected class showed decreases in travel time. For the most part increases in travel time were seen in links leaving from nodes 20, 21, 22, and 24 as well as nodes 15 and 14 which all belong to the high income class. Although this may appear to be an uneven distribution of benefits, the goal of these cordons is to reduce the gap between the two classes, which this toll does much more effectively than the one previously discussed.

Cordon Toll 4 (CT4) showed the least fluctuations in TSTT change with increases in travel time when compared to all other tolls simulated. The cordon for this toll was formed around nodes 11, 12, 13, 14, 23, and 24, encompassing the southeast portion of the city. Out of these nodes only node 11 belongs to the protected class.

Table 8: TSTT and TSC for Cordon Toll 4

Sioux Falls (Cordon Toll)					
Toll Factor (.01hr*$)	Toll ($)	TSTT(.01hr*vph)	TSC(.01hr*vph)	Delta(.01hr*vph)	Cost Due to Tolls (.01hr*vph)
0	0	7,480,005.31	7,480,005.31	-	-
4.16	1	7,489,626.07	7,745,169.77	9,620.76	255,543.71
4.16	2	7,507,109.78	8,011,301.74	27,104.47	504,191.96
4.16	4	7,514,444.61	8,519,500.60	34,439.31	1,005,055.99
4.16	8	7,514,493.85	9,524,605.86	34,488.54	2,010,112.01
4.16	16	7,514,507.23	11,534,731.23	34,501.92	4,020,224.00

Table 8 shows the increases in TSTT and TSC. As the charge to users increased the change in travel time becomes relatively small for charges of $4 and higher. This is unlike any of the other cordon combinations that were tested. In terms of overall system performance these changes are positive, because even at very high charges users the systems overall TSTT is not high. All other cordons tested had time differences when compared to the base case of at least 100,000 .01hr*veh, therefore this toll performs well at high toll values. TSC will increase as a toll increases because of the way that it is calculated, as a higher charge will have a more significant impact on the BPR function calculation, therefore all cordons see significant costs due to tolls at higher charges.

With regards to overall link performance, the number of links affected was lower than in the two previous tolls discussed. Only 24 links saw significant changes in flow, with average increase and decreases in flow for the affected links being much lower than the previous two tolls discussed. At the charge of $1 the amount of links that saw a negative change in travel time was double that of those that saw a positive change. As the charge increased these patterns prevailed, average changes in flow and travel time were lower compared to other tolls, and the number of links affected was also lower. Furthermore, the number of links affected stayed constant after the $4 charge which would explain why changes in overall TSTT were so low.

Table 9: Effect of CT4 on Link and Flow Performance

$1 Toll		
	Flow (vph)	Time (.01hr)
Average Increase	195.75772	0.2165112
Average Decrease	-317.1418	-0.41924
Count Increase	12	12
Count Decrease	12	6

On a specific link performance basis, only saw improvement for links originating from node 24 and a few links starting from nodes 21, 13, and 23. All of these nodes are high income nodes and except for node 21 they make up the cordon, showing that the main benefits imposed by this toll are on higher income groups. Conversely, the most affected links in terms of travel time were originating from links 5, 6, 8, and 9 all lower income nodes. Meaning that despite the overall consistently positive performance in terms of system TSTT, a deeper dive into what's happening at the link level shows that this cordon does not provide benefits that agree with the objective of reducing the gap in equity between both groups.

4.2 Multi-Class Simulation

Multi-class simulation provided the opportunity to look at how TSTT and TSC varied by class, making it possible to distinguish between an equitable toll and one that is just beneficial for the whole system. It also provides a more realistic analysis of drivers' travel costs because not everyone values their time in the same manner and splitting users into classes allows this distinction to be made. In this section a comparison between the single class and multi-class cordon tolls that were discussed in the previous section will be done to evaluate how multi-class analysis can reveal more about the effectiveness of each toll. As mentioned earlier the toll factor used is different for depending on whether the node on the link entering the cordon belongs to the high or low income group. The toll factor for the high income group was 2.77 .01hr/$ and the toll factor for the low income group was 4.62 .01hr/$.

Beginning with CT1, the high income class was defined as Class 1 and the lower income class was defined as Class 2. Changes in system TSTT and TSC were minimal when compared to the single class simulation. Again, there were improvements in TSTT for the overall system at the two lowest toll charges, but looking at the specific class values of time and cost helps to identify how these benefits are being distributed.

Table 10: Multiclass Results of TSTT and TSC for CT1

Toll ($)	**Class 1 TSC (.01hr*vph)**	**Class 2 TSC (.01hr*vph)**	**Class 1 TSTT (.01hr*vph)**	**Class 2 TSTT (.01hr*vph)**	**Class 1 CDT (.01hr*vph)**	**Class 2 CDT (.01hr*vph)**	**Delta C1 (.01hr*vph)**	**Delta C2 (.01hr*vph)**
0	3,939,945.50	3,540,867.50	3,939,945.50	3,540,867.50	-	-	0	0
1	4,045,524.25	3,737,618.00	3,911,681.50	3,532,008.50	133,842.75	205,609.50	-28264	-8859
2	4,171,637.00	3,949,782.75	3,911,390.75	3,540,316.00	260,246.25	409,466.75	-28554.75	-551.5
4	4,446,965.00	4,372,776.50	3,926,471.50	3,576,519.50	520,493.50	796,257.00	-13474	35652
8	5,056,997.00	5,269,804.50	4,041,502.25	3,802,546.25	1,015,494.75	1,467,258.25	101556.75	261678.75
16	6,203,841.00	6,909,130.50	4,327,278.50	3,974,614.00	1,876,562.50	2,934,516.50	387333	433746.5

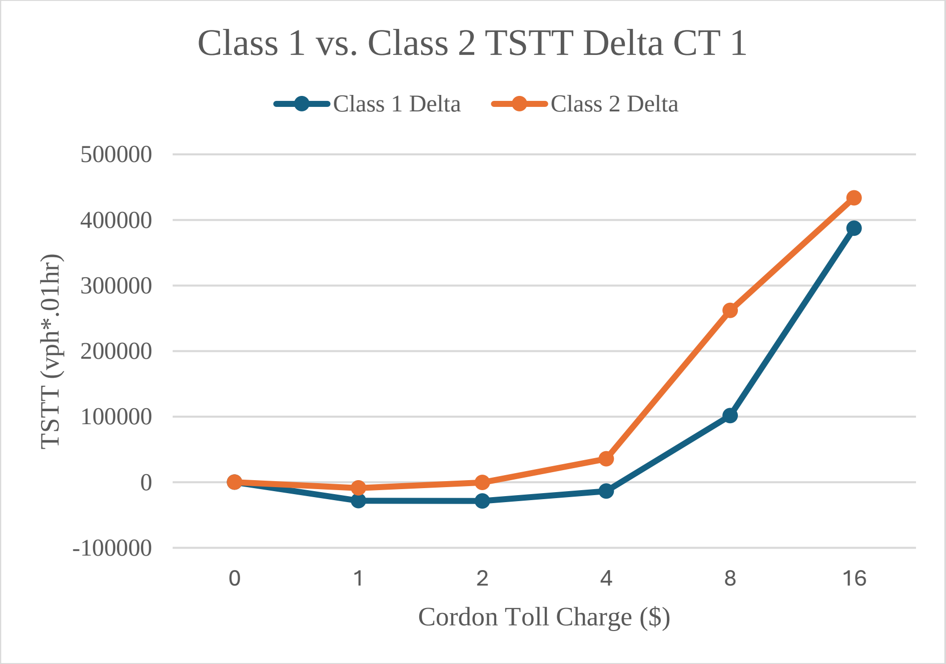

Figure 6: Multiclass Results of TSTT and TSC for CT1

In the single class simulation of this cordon, looking at specific links showed that the benefits of the cordon were felt more by the links whose tail belonged to the one of the nodes forming the cordon and that links starting at nodes 6, 7, and 8 saw negative effects in travel time. The multiclass simulation confirms this, while also giving insight into some effects that were not available when running the single class simulation. Cost and travel time amongst both classes are similar in value across all the tolls charged. The benefits, though, are not spread evenly amongst both classes. Cost due to the toll was significantly greater for the lower income class. The table also shows how the share of travel time changes is divided amongst both classes. From the $1 and $2 it’s clear that travel time savings were made for the whole system overall, but most of these savings benefited the high income class, and as the toll value increases the increase in TSTT with regards to time is greater for the lower income class. As a result, the multi class simulation shows that although CT1 provides the most TSTT savings for the system, these are not spread out evenly, leading to the conclusion that this cordon toll does not align with the description of an equitable toll in Chapter 3.

Like CT1 changes in TSTT and TSC were minimal between the two different simulations. The overall system performance of this cordon with respect to changes in TSTT and TSC was poot, with significant increases in both.

Table 11: Multiclass Results of TSTT and TSC for CT5

Toll ($)	Class 1 TSC (.01hr*vph)	Class 2 TSC (.01hr*vph)	Class TSTT (.01hr*vph)	Class 2 TSTT (.01hr*vph)	Class 1 CDT (.01hr*vph)	Class 2 CDT (.01hr*vph)	Delta C1 (.01hr*vph)	Delta C2 (.01hr*vph)
0	3,939,945.50	3,540,867.50	3,939,945.50	3,540,867.50	-	-	-	-
1	4,155,595.00	3,782,700.00	3,985,259.00	3,574,527.75	170,336.00	208,172.25	45,313.50	33,660.25
2	4,357,849.50	4,008,959.75	4,017,805.00	3,608,323.50	340,044.50	400,636.25	77,859.50	67,456.00
4	4,787,346.00	4,472,791.50	4,138,569.50	3,694,743.00	648,776.50	778,048.50	198,624.00	153,875.50
8	5,718,438.00	5,410,798.50	4,476,641.00	4,000,407.00	1,241,797.00	1,410,391.50	536,695.50	459,539.50
`16	7,558,779.50	7,200,943.50	5,229,737.50	4,682,373.50	2,329,042.00	2,518,570.00	3,618,834.00	1,141,506.00

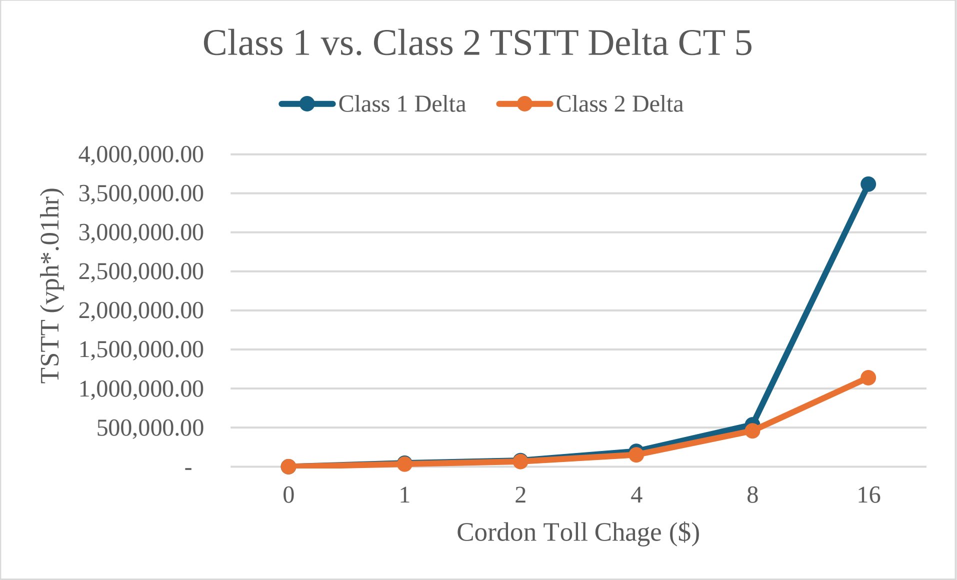

Figure 7: Changes in TSTT for Class 1 and Class 2 at increasing toll charges

Figure 12 shows the increase in TSTT for both groups. As the toll became higher the overall TSTT of the system increased. At lower toll values, the difference between the untolled TSTT and the TSTT for given toll values was similar for both classes. As the toll increases to $8 it is clear that the high income group is receiving most of the negative effects in terms of travel time increase. At the highest toll value, more than half of the increase in TSTT to the overall system can be attributed to Class 1. Despite the significant difference in travel time increase between the two classes, the cost due to the tolls is distributed more evenly between the two classes and it is higher for Class 2. The multi class analysis confirms what was previously seen at the link level in the single class simulation. The benefits in travel time savings for this cordon toll are much greater for the Class 2 than Class 1. This makes the toll more equitable as the benefits are uneven but they favor the lower income group. Despite this, it would be hard to justify the implementation of this toll, specially at higher charges. The system performance is very poor. Cost due to tolls was know to be high from the single class simulation and the second analysis shows that it is marginally worse for the lower income group. Finally, the variation in travel time being so much higher for one class than the other would most certainly make it an unappealing alternative to drivers belonging to Class 1.

The previous two cordon tolls provided different benefits to the system, but neither provided good enough changes to the protected class or to the total system TSTT, such that they could be defined as equitable tolls, and they would provide a suitable alternative for users of the network. Looking at the other eight cordons that were simulated two things stand out: Class 1 receives better travel time savings at the $1 and $2 toll charges in all but one toll and the cost due to the tolls is higher with every cordon that was tested on the network. This meant that out of all the cordons that were tested none met the objective of decreasing the protected population's TSTT by a larger amount than the unprotected group and providing TSTT improvements for the whole system. Whenever the TSTT of the system decreased most of this benefit was felt by Class 1. Conversely, if the effects of the toll were slightly more beneficial for Class 2, then the TSTT of the system overall was increasing.

The cordon that came closest to achieving this goal was Cordon Toll 9 (CT9) which was made up of the area bounded by nodes 7, 8, 16, and 18, which are all lower income nodes.

Although the system's TSTT never decreased at any of the toll charges, the rest of the changes were positive in terms of an equity perspective.

Table 12: Multiclass Results of TSTT and TSC for Cordon Toll 9

Toll ($)	**Class 1 TSC(.01hr*vph)**	**Class 2 TSC (.01hr*vph)**	**Class 1 TSTT (.01hr*vph)**	**Class 2 TSTT (.01hr*vph)**	**Class 1 CDT (.01hr*vph)**	**Class 2 CDT (.01hr*vph)**	**Delta C1 (.01hr*vph)**	**Delta C2 (.01hr*vph)**
0	3,939,945.50	3,540,867.50	3,939,945.50	3,540,867.50	-	-	-	-
1	4,053,060.25	3,679,369.25	3,965,599.75	3,555,973.25	87,460.50	123,396.00	25,654.25	15,105.75
2	4,168,853.75	3,815,665.75	3,999,267.75	3,576,049.75	169,586.00	239,616.00	59,322.25	35,182.25
4	4,400,445.50	4,076,129.75	4,082,095.75	3,635,179.25	318,349.75	440,950.50	142,150.25	94,311.75
8	4,810,797.00	4,575,674.50	4,257,508.50	3,707,285.00	553,288.50	868,389.50	317,563.00	166,417.50
16	5,368,648.50	5,438,604.00	4,289,918.50	3,722,092.75	1,078,730.00	1,716,511.25	349,973.00	181,225.25

Table 12 indicates how both classes reacted to the implementation of this cordon. As stated above, similar to all the other tolls the cost due to tolls was higher for the protected class, but the difference between Class 1 and Class 2 was one of the lowest out of all the tolls tested. This resulted in the difference between travel time cost for Class 1 and 2 staying relatively equal for all toll charges, except for the $16 charge. More importantly, the increase in TSTT for the system always increased but it did so in small amounts compared to the other cordons tested. At all of the charges tested, it resulted in more positive effects, lower increases in travel time, for the protected class than for the unprotected class. This is in part due to the fact that the cordon was placed around lower income nodes. At the link level, links originating from nodes 6, 7, and 8 saw the highest decreases in travel time, and these are all lower income nodes. Most of the increase in travel time was seen in links with a tail node belonging to the high income group. Therefore, although the benefits are not evenly distributed, they favor the protected population in a way that no other cordons tested do. The increase of system TSTT conflicts with the goal of reducing congestion for users of the network, but all other effects favor the protected population, making it the most equitable toll tested, as the overall objective of these cordons is to reduce the inequality gap not system TSTT.

Chapter 5: Conclusion

As urban areas grow and the number of people living in these areas rises, users of the transportation network and existing infrastructure face several issues. From increasing congestion, more notable noise pollution, and higher emissions produced these issues have a significant effect on the quality of life of citizens of these areas. As a result, several transportation projects focus on ways to combat these problems to make commutes shorter, travel more efficient, and find ways to make cities more livable.

Congestion pricing and tolling is one of the methods used to provide solutions to these problems. Tolling of facilities has been around for a long time, frequently used as a way to generate funds for future improvements to the transportation infrastructure. Over the last fifty year congestion pricing has been implemented around the world with different aims and strategies used. From HOT lanes which provide congestion-free alternatives to their users to cordon or area tolls that charge users for entering densely populated areas at given times of day, these systems have been largely successful at decreasing congestion, emissions and generating revenue for future projects.

Despite their success, in many parts of the world it has taken a long time for these projects to move forward, with this being one of the biggest hurdles to overcome before any congestion scheme can be implemented. Many see them as a restriction on people’s freedom to move or a system that only benefits those who are able to afford the charges. These concerns are justified. An efficient transit system is important for a congestion pricing scheme to be implemented because it provides an alternative for people who cannot afford to pay the toll every time they enter the area. Residents of these areas and emergency services will either enter the zone more or are a basic service for those living within the zone, therefore they cannot be paying the same as other users. People also worry that in the long run these schemes will end up increasing inequality because lower income users are more likely to end up with higher travel times because of their inability to pay the tolls.

These concerns have led many to seek ways to ensure that equity is considered when these congestion pricing is suggested as an alternative. Equity is a hard topic to tackle because it is usually associated with fairness and what is deemed fair will vary depending on who defines it. Different types of equity should be considered and the most relevant to the project should be chosen. In addition, it is also important to use a social equity theory as guidance for decisions made during the process in accordance with the type of equity considered and the proposed benefits that are to be achieved.

In this thesis, the concerns on congestion pricing and guidelines on how to implement equity are applied to test multiple cordon tolls on the Sioux Falls network, in a single class and multi class analysis. Vertical equity and Rawl’s Theory of Justice were chosen as the equity theory and type to define what an equitable toll was. The aim of this toll was to focus on providing more benefits to the lower income or protected population, even if this was at the cost of the whole system’s performance, these benefits were measured in terms of TSTT and travel time within specific links. It also meant that benefits do not have to be distributed evenly amongst both groups.

The single class analysis showed that the addition of a cordon toll to the system could result in lower a lower TSTT overall depending on where it was placed. Most of the cordons tested showed no improvement in travel time and those that did improve did so only for the $1 and $2 charges. By looking at specific link flows and travel times, it became clear that the clear beneficiaries of the cordon toll where users who drove on links that originated from nodes on the cordon, this was true for all cordons tested. Other links in the system were also affected, with travel times and flows changing all over the network as drivers adjusted to the higher cost of using the tolled links. Equitable tolls where those that had decreases in travel time and flow on links that did not start or end at nodes making up the cordon, but more detail was still needed. Multi-class analysis provided a more accurate idea of what users would experience when these tolls were implemented, because it considered the value of travel time for different users based on their income. This analysis provided different results than the single class test. Tolls that had previously seemed beneficial and equitable, such as CT1, proved to only be providing system level benefits, with the lower income group receiving less of the benefits. None of the tolls tested lowered the TSTT of the system while also providing a distribution of benefits that favored the protected population or that at least resulted in equal travel time savings for both classes. The best performing toll form this analysis was deemed to be CT9 which did not provide reductions in system TSTT but was the toll that provided the lowest increases in TSC for the low income group. Although travel time increased on this toll, the distribution of favored the low income group, with a lower increase at all toll values when compared to the high income group.

Formulating an optimization problem that finds the best toll value for cordon configurations should be considered in the future as this can find the most equitable solution to a given set of objectives. Equity theories considered will still affect what the optimal toll configuration is but will result in a more precise solution to the question of what can be considered an equitable application of a cordon toll to a system.

Overall, this thesis sought to provide an equitable solution to the application of cordon tolls to a system. TSTT and TSC values for the system serve as a useful starting point to determine the effectiveness of the toll in decreasing travel time. The use of multi-class simulations provided more detail and insight into how different people were being affected and should be used if possible because results are completely different between using one class and using two. Link-by-link analysis should also be applied to determine whether a toll is effective or not, especially in the single-class case, because it provides detail that is not available when TSTT is calculated for the system or even for different classes.

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