CATM
Center for Advanced Transportation Mobility

EQUITABLE DYNAMIC PRICING OF EXPRESS LANES

FINAL REPORT

SEPTEMBER 2022

AUTHORS
Venktesh Pandey
Bader G. Alamri
Hadi Khoury
Mary Bakre
North Carolina Agricultural and Technical State University

US DEPARTMENT OF TRANSPORTATION GRANT 69A3551747125

DISCLAIMER

1. Report No.

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
Equitable Dynamic Pricing of Express Lanes

5. Report Date
September 13, 2022

6. Source Organization Code

7. Author(s)
Pandey, Venktesh; Alamri, Bader G.; Khoury, Hadi; and Bakre, Mary.

8. Source Organization Report No.
CATM-2022-R9-NCAT

9. Performing Organization Name and Address

Center for Advanced Transportation Mobility
Transportation Institute
1601 E. Market Street
Greensboro, NC 27411

10. Work Unit No. (TRAIS)

11. Contract or Grant No.
69A3551747125

12. Sponsoring Agency Name and Address

University Transportation Centers Program (RDT-30)
Office of the Secretary of Transportation–Research
U.S. Department of Transportation
1200 New Jersey Avenue, SE
Washington, DC 20590-0001

13. Type of Report and Period Covered
Final Report:
Feb 2021– Dec 2021

14. Sponsoring Agency Code
USDOT/OST-R/CATM

15. Supplementary Notes:

16. Abstract

Express lanes mitigate traffic congestion by providing a time-reliable alternative and exploiting travelers' willingness to pay to generate revenue for infrastructure projects. Over the last decade, equity and fairness issues for express lanes have been considered; however, there is a lack of guidance on the design of equitable discounts. In this article, we present a modeling framework for the analysis of equity issues with express lanes for tolls optimized for different objectives. Through simulation-based optimization of tolls using reinforcement learning, we show that the choice of dynamic tolls impacts the delay differentials across different groups. We find that higher toll values and higher demand worsen the delay differentials across travel groups. We also prove that discounts proportional to travelers' value of time address delay differentials across the travel groups, where the optimal discounts may be a function of current toll and travel time savings. The analysis of tradeoffs between equity, revenue, and delay reveals that equitable discounts may result in up to 34% loss of revenue and up to 9% increase in delay. Research findings suggest (a) designing discounts proportional to VOT which can be correlated with income groups and (b) balancing the tradeoffs by carefully identifying the agency's priorities.

17. Key Words
Express lanes, Equitable discounts, Congestion Pricing, Transportation Equity

18. Distribution Statement

Unrestricted; Document is available to the public through the National Technical Information Service; Springfield, VT.

19. Security Classif. (of this report)
Unclassified

20. Security Classif. (of this page)
Unclassified

21. No. of Pages
38

22. Price
…

Form DOT F 1700.7 (8-72)   Reproduction of completed page authorized

TABLE OF CONTENTS

EXECUTIVE SUMMARY

Priced managed lanes or express lanes are facilities that provide reliable travel time in exchange for a toll. The presence of tolls on these facilities raises potential equity concerns: are the economically-disadvantaged or poor travelers worse off due to express lanes? Equity concerns align with the nationwide emphasis on creating equitable transportation systems that meet everyone's needs and create equal access and mobility for all. Equity and fairness issues for express lanes have been considered over the last decade leading to arguments in favor of equity where toll lanes provide an option to pay a toll rather than requiring toll mandatorily. Recent studies such as the analysis of I-405 lanes reported that low-income travelers indeed use the express lanes when the need presents. However, there is a lack of guidance on the design of equitable discounts.

This report presents the framework for analyzing equity concerns with the dynamic toll pricing plan on managed lanes system from a modeling perspective. The report addresses research gaps in the literature. First, there is no clear guidance on the design of differential prices and discounts. A differential pricing method based on travelers' value of time (VOT) is proposed, and it is proven that VOT-proportional discounts address equity differentials across the delay, where the discounts may be a function of current toll and travel time savings at a given gantry. Second, the report analyzes the different toll profiles that may contribute to the jam-and-harvest characteristics of dynamic tolls, an unintended consequence where creating more jams on the regular lanes in earlier time periods to harvest more revenue towards the latter part. Through simulation-based optimization of tolls, we argue that the choice of dynamic tolls impacts the delay differentials across different groups. We find that higher toll values and higher demand worsen the delay differentials across travel groups due to more congestion on general-purpose lanes. Finally, holistic considerations of equity are incorporated in our analysis by accounting for a simulation-based model that incorporates varying toll optimization objectives and component models such as lane choice. The evolution of traffic on the corridor is modeled using a macroscopic multiclass cell transmission model, while the lane choice is modeled by considering the utility of travelers being deterministic or stochastic. The best toll policy was determined using a reinforcement learning model that optimizes the dynamic toll to maximize revenue or minimize total system travel time.

The findings from the study provide the following guidance. First, a discount proportional to the traveler's value of time can result in a more equitable distribution of delays across the travel groups. Such discounts can be implemented in practice by assessing the value of time distribution through revealed-preference surveys and analysis of toll data. Once estimated, the VOT distribution can be correlated with income levels and discounts can be offered based on the traveler's income group (like is done in a few pilot studies such as I-10 Express Lanes in California). Second, for the simulation case studies it is found that if equity is prioritized, it can result in a loss of revenue by up to 34%, and an increase in total system delay by up to 9%. The loss of revenue is higher due to the elimination of the jam-and-harvest phenomenon under the presence of equitable tolls. This quantification of the "price of fairness" can enable transportation agencies to make effective decisions on weighing equity relative to other priorities of the agency.

Being a simulation-based analysis, the study has a few limitations such as the exclusion of departure time choice decisions, not modeling the complexities of lane change behavior, and considering equity in terms of delay distribution instead of other metrics that might be difficult to measure. Addressing these limitations is left as part of future work. Despite the limitations, the findings shed light on how future discounts can be designed for equitable benefits using express lanes.

BACKGROUND

Current evidence on transportation systems demonstrates that disadvantaged members of society disproportionately receive lower benefits or suffer additional costs/externalities from current transportation policies (Bills and Walker, 2017). Furthermore, emerging transportation technologies and alternate revenue-generation mechanisms have raised concerns associated with the differential impacts of new congestion pricing and taxation mechanisms.

Congestion pricing methods incentivize travelers to choose other modes of transportation, travel at different times, or choose alternative routes; therefore, reducing traffic, especially during rush hour (FHWA, 2022). In addition, congestion pricing is an essential source of funding for various transportation infrastructures, managing traffic demand, and reducing congestion (Ecola & Light, 2009). There are two main categories for congestion pricing, strategies involving tolls and strategies that do not. Types of the former category include corridor pricing (pricing part of the road such as express lanes) or cordon pricing (toll on a defined geographic area such as entire roadway, zone, or region). The latter category, strategies that do not involve tolls, includes priced parking, vehicle sharing, and dynamic ridesharing, and pay as you drive. Pricing increases throughput of vehicles during peak hours, making traffic flow smoother.

This report is concerned with the equity impacts of congestion pricing on express lanes. Priced managed lanes or express lanes are commonly used to mitigate traffic congestion by providing a reliable travel time in exchange for a toll. As of March 2021, there are 73 operational managed lane projects and 34 projects in various stages of development/implementation across the United States (n.a., 2020a). These lanes provide a congestion-free alternative and also generate the much-needed revenue for infrastructure projects. Dynamic tolling is commonly adopted for pricing these facilities where the tolls vary with either the time of day or the congestion pattern to ensure a desired level of service on the managed lanes (Wood et al., 2020). The state of North Carolina opened its first express lane project I-77 Express Lanes in 2019—a 26-mile long corridor linking Mooresville to uptown Charlotte on the I-77 freeway. I-77 Express lanes charge dynamic tolls based on congestion patterns to “ensure a predictable, higher-speed commute and allow traffic to flow at a minimum of 48 mph during peak travel times” (n.a., 2020b).

The presence of tolls on express lane facilities raises potential equity concerns: are the economically disadvantaged aka poor travelers worse off due to express lanes? Equity in transportation refers to the equal distribution of public services for all communities with no exemption. These services should have an equal impact on different users' quality of life and how they travel from one location to another. Equity in transportation should meet users' needs in each community while minimizing traffic and faster trips. Real-world practitioners are keenly aware of the equity pitfalls that dynamic tolls present. Commonly the equity concerns are addressed as a public relations problem (Wang et al., 2012) or an education problem (Giuliano, 1992), with solutions that allocate toll revenues to projects that visibly increase equity or subsidize public transit.

There are additional arguments in favor of equity for express lanes. For example, it is suggested that these lanes are more equitable than the do-nothing option since they provide a choice to escape the congestion; if there is no choice, poor travelers are impacted the worst due to the possibilities of a lost job or a late fee at the daycare (FHWA, 2022). Additionally, the findings from the surveys suggest that the differential impacts of tolls are related more to the schedule flexibility of users and the availability of alternate routes than to income (FHWA, 2022). Evidence on current managed lanes shows that a properly designed pricing scheme may not disadvantage low-income travelers, such as the case studies on SR-91 express lanes and I-15 express lanes in California where low-income do use the express lanes, albeit with reduced frequency relative to high-income travelers. Additionally, these lanes provide rebates to transit vehicles, and low-income travelers are more likely to use transit. Finally, income is not the only defining criterion for who uses the managed lanes. For the MnPASS lanes on I-394 in Minnesota, MN it was found that residential location has a significant effect on the usage of lanes where traveling long distances is strongly correlated with the higher use of the managed lanes (Patterson and Levinson, 2008).

Like any market good, the managed lanes are horizontally equitable: high-income travelers pay the most (in average and total tolls) and receive the most benefit. However, access to transportation is a fundamental good and every transportation policy should be evaluated using the lens of whether the policy shows equal respect to all citizens (Helsel et al., 2020).

Poor travelers commonly cannot afford the price to be paid for choosing the reliable travel-time alternative that managed lanes offer. During peak periods, tolls may be very high; for example, the tolls on express lanes in Virginia reached as high as $47 during the peak periods (Lazo, 2018; Sigo, 2018). Additionally, because express lanes are commonly built on expressways, transit routes that commonly serve poor neighborhoods and streets in the city center do not benefit from using the lanes. Furthermore, several of the current express lane projects are financed through public private partnerships (PPPs), such as I-77 Express Lanes in Charlotte, MoPac Express Lanes in Austin, etc. Under a PPP, a private entity handles the design, construction, planning, operations, and management of managed lanes over a time period typically spanning multiple decades (NCHRP, 2016). Different toll agencies assign different weightage to various objectives for managed lane operations, some of which may not be equitable. For example, a private entity might prioritize revenue maximization over ensuring the least possible delay for travelers, which raises potential equity concerns for roadway operations.

Need for Transportation Equity

In transportation, equity considerations are required in various forms depending on the type of decisions being made. Equity is commonly considered in the following decisions:

1. provision of facilities and services (such as the provision of ramps on sidewalks for people with disabilities) (Dempsey, 1990; Hershey et al., 2010),
2. design of usage fees and regulations for the same (such as congestion pricing, parking fees, and land-use costs) (Helsel et al., 2020; Hall, 2018),
3. accessibility across population groups (such as quality and frequency of transit services through poor neighborhoods or lack of short-window delivery options to disconnected neighborhoods during COVID pandemic) (Pathak et al., 2017),
4. mitigation and compensation for externalities and other negative impacts that disadvantage certain population groups more than others (such as excessive noise and

air pollution for neighborhoods near highways, or displacement of population groups for building transportation projects),

5. design of transportation projects and their impacts on possible disruptions of community cohesion, economic vitality, and use of public facilities, and
6. enforcement efforts related to transportation facilities and services (such as discussions around how poor travelers who are less likely to own toll tag and thereby pay more for toll roads).

Necessitated by federal environmental justice regulations to incorporate equity in federal projects, current guidance on ensuring equity in transportation planning follows the standard five-step procedure shown in Figure 1(a) (Twaddell and Zgoda, 2020). This procedure involves quantifying disparate impacts of transportation policies through models that capture the behavior of real-world systems into analytical and simulation frameworks capable of analyzing differential impacts of transportation policies on the access and mobility of different population groups. Once these impacts are identified, transportation incentives are then used to mitigate the impacts. For example, special bus routes may be designed to go through poorer neighborhoods (Sanchez, 2008), discounts may be provided for low-income travelers to use toll lanes (E. Metro, 2021), or coupons may be given for access to bike-share programs (Hoe and Kaloustian, 2014).

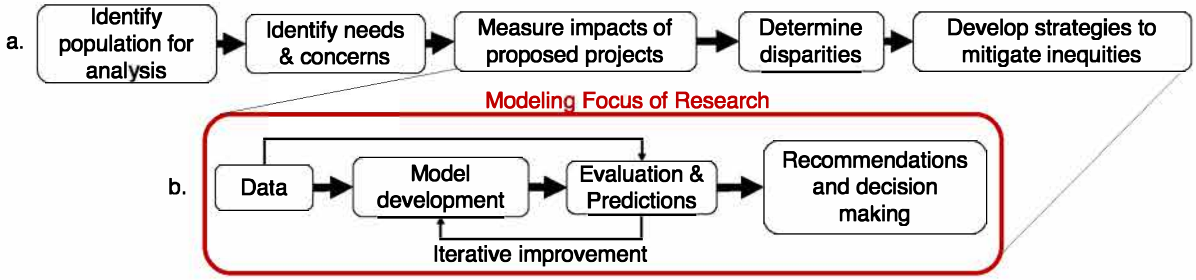


Figure 1: (a) Five-step procedure for analyzing equity concerns in transportation projects (Twaddell and Zgoda, 2020), and (b) the modeling approach for addressing equity concerns as the focus of this project

For a fair distribution of services for all communities, transportation agencies need to (Litman, 2021)

- Locate where congested roads are
- Provide high-quality transportation planning
- Land availability to add managed lanes in congestion roadways

- Access and exit points for managed lanes should meet users' needs and movement
- Availability of space for the creation of more lanes within existing managed lanes
- Determine affordable toll charge for all users
- Pay attention to people with disability and no cars

DESCRIPTION OF PROBLEM

The goal of this research is to develop guidance on addressing equity concerns with express lanes from a modeling perspective (Figure 1(b)). It is well understood that models make simplifying assumptions for tractability on large scales (Bender, 2000); however, improper characterization of factors affecting equity can trigger the models to make recommendations that are broadly inequitable (Gordon, 2021; Bills and Walker, 2017). Furthermore, equity-evaluation models rely on measuring equity, which in itself varies significantly across applications.

In particular, the objective of this study is to analyze the equity aspects of express lanes focusing on the design of dynamic tolls. The study seeks to fill three gaps in the literature:

1. First, it has been suggested that to create long-term equity benefits for express lanes, agencies should consider a cumulative impact across the entire population in the region (Ungemah, 2016). Some agencies are considering lifeline tolling (where individuals who qualify for discounted rates on certain government services can avail of similar discounts for using express lanes) and differential pricing (where different users pay different tolls for the same facility). However, there is no clear guidance on how those differential prices and discounts should be designed and what is the impact of those discounts on the travel behavior of different groups.
2. Second, it has been shown that toll policies that optimize for revenue can have unintended consequences such as creating more jam on the regular lanes in earlier time periods to harvest more revenue towards the latter part, a phenomenon termed *jam-and-harvest* (Pandey and Boyles, 2018). A preliminary analysis showed that revenue-maximizing tolls that cause jam-and-harvest (JAH) significantly impact low-income travelers and impart all the travel-time savings to high-income travelers who

can afford to pay to avoid the congestion. There is a need for a clear and transparent analysis of how different toll policies can unintentionally cause JAH.

3. Last, while the issues of equity have been analyzed in congestion pricing settings, there is a need for a systems-level approach for analyzing equity. This includes analyzing whether the presence of tolling on express lanes forces low-income travelers to adjust their travel patterns differently than high-income travelers, whether toll revenues are used equitably, whether the routes of alternate modes such as transit are factored in the design of toll prices, and whether building more express lanes is the best method to address congestion issues than other more sustainable alternatives such as bike routes and mass transit. Time poverty (Helsel et al., 2020) is another concept that is relevant for equity discussions—travelers are not only income poor but are often time-poor and that requires accounting for the value of their time relative to their income levels while designing tolls. There is a need for integrating broader equity definitions in discussions surrounding managed lane facilities.

Currently, there is a lack of translation of equity metrics and goals in transportation decision-making processes. Commonly used traffic control optimization models prioritize efficiency (such as minimizing total system travel time) over equity impacts like the differential impact of toll prices across travel groups. Prior research has shown that there is a trade-off between equity (also referred to as fairness) and efficiency in a given congestion pricing system (Helsel et al, 2020). This trade-off is commonly quantified as the price of fairness, defined as the loss of efficiency obtained by a “fair” policy relative to the most efficient policy (Bertsimas et al., 2011). While the price of fairness has been analyzed for problems associated with resource allocation, airport pricing, and drug testing (Aprahamian et al., 2019; Gutjahr and Fischer, 2018), conducting price of fairness analyses for different equity metrics across various transportation systems is still missing. The research question stemming from this gap is: how should the trade-offs between equity and efficiency be considered towards designing incentives for emerging traffic control and congestion pricing systems? (Nagatani, 2022)

The optimization of tolls for express lanes can be done using various pricing methods including dynamic programming (Wang et al., 2012), feedback integral control), single-bottleneck model based analytical calculations (Hall, 2018), dynamic traffic assignment-based optimization (Zhang et al., 2018), model predictive control (Tan and Gao, 2018), and deep-reinforcement learning (Pandey et al., 2020). See Lombardi et al. (2021) for the review of models for the pricing of express lanes. These models demonstrate the complexity of tolling operations due to their dynamic nature. However, there is a lack of research on equitable benefit of designed tolls.

In particular, Hall (2018) investigated the practical relevance of generating a Pareto improvement by estimating the distributional and aggregate consequences of congestion pricing. The findings showed that Pareto efficiency is possible by tolling a portion of lanes even before spending the revenue towards public welfare, where it was found that travelers with higher value of time and higher flexibility benefit the most. While the economic analysis offered a useful insight, it is unclear how these results can be extended for networks with multiple entrances and exits and for different tolling objectives.

Building on the gaps in the literature, **the key research questions addressed in this report are**:

- With regards to dynamic pricing on express lanes, how can we define equity and how can we evaluate what policies are equitable?
- What is the current modeling approach toward quantifying the disparate impacts across users of managed lanes? In addressing so, we provide a bridge between approaches that have been developed in non-overlapping fields of welfare economics, transportation welfare, fairness and justice, and mechanism design
- Finally, how can we design discounts and differential tolls that address the equity impacts with current express lane projects?

LITERATURE REVIEW

Evaluation and Formulation of Equity

The formulation of equity starts with defining congested roadways and identifying how to minimize traffic flow in these locations (Litman, 2021). Equitable transportation planning provides accessibility to services for different locations without the exemption of people who use them. Equity in transportation should consider people with a lack of access to transportation, people with disabilities, and low-income users. Congestion pricing can be formulated based on many factors such as types of vehicles, time of day, number of people in each vehicle, and path (direction) of users (Litman, 2021). Pricing should be affordable to enhance users' use of express lanes that provide faster movement. Toll charges can be adjusted while considering users with low income, disability, and/or high vehicle occupancy by allowing such users to pay less fees than regular users. Researchers have identified that poor people pay a high portion of their annual income while rich people pay less (Ecola & Light, 2009). The main concern about equity is the cost associated with the service and benefits that the society members receive. Congestion pricing planning should look at disadvantaged groups and provide offers and exemptions based on age, gender, and communication ability (Ecola & Light, 2009).

Below are some of the factors that need to be considered to help formulate equity in managed lanes (Madi, 2013):

- Define the impacts of congestion pricing on people and analyze them before selecting toll charges.
- Measure equity in the existing system that the new system will replace. It is hard to achieve perfect equity in any system. Therefore, addressing problems with the existing system to avoid problems with a new system to have equitable services for all users.
- Improve public transportation services to have high quality for all users.
- Help people understand the benefits of managed lanes and define the groups affected by this project type.
- Consider equity vs. efficiency and how to manage the two factors.
- Consider the net equity outcome, which is the critical measure of the project.

Equity in transportation and congestion pricing can be evaluated on many aspects. It is hard to achieve fairness among all users, and many studies approve that some elements of the planning will not be equal among all people such as certain groups can be affected by congestion pricing because of where they live and work (Ecola & Light, 2009). Congestion pricing might be equitable in some parts and less in others. Some people might pay a different amount in congestion tolls due to the areas where they live in or work. Therefore, congestion pricing does not fare well in terms of horizontal equity (Ecola & Light, 2009). Equity should not be evaluated only based on income; consideration of age, environment, gender, and trip directions will help achieve all users' equity.

Litman (2021) suggests four dimensions that impact equity analysis in transportation systems:

- First, we answer what type of equity is desired. Vertical equity requires the allocation of benefits and costs that favors disadvantaged people. In contrast, horizontal equity considers all users on the same level field and applies the same rules to everyone. Vertical equity is justified and desired when access to opportunities is argued as a necessity.
- Second, we answer what impacts we are measuring of a given transportation policy. Agencies typically care about the impacts on congestion level, pollution, crash risk, community cohesion, economic opportunities, and employment and business opportunities. Equity considerations should define the impacts that agencies care about.
- Third, we answer to what disaggregation we are measuring the impacts. For example, disaggregation of the defined impacts can be measured per adult, per household, per commuter in peak period, per vehicle-miles-traveled, per trip, per dollar fee, or per dollar of subsidy.
- Finally, we answer how we are categorizing people. It can be done by disability, age, household type, race, ethnic group, income levels, neighborhood, mode of travel, or trip type. While some categories are easy to integrate within models, it can be a hard process to account for all categories.

The core recommendation from equity analysis literature is that there is no single way to evaluate transportation equity—it is a process that is agency-specific and involves the public and all stakeholders.

Guidance from Existing Express Lanes

Current express lanes across the United States include some considerations for discounts. Virginia Department of Transportation has a long-time partnership with

Transurban to manage and operate the 495, 95, and 395 Express Lanes (Transurban, 2022). This type of partnership will run until 2087, and it in effect 24 hours a day and seven days a week. Express Lanes use dynamic pricing to ensure that customers are moving and along with this dynamic pricing, travelers will have different speed limits on different Express Lanes (Transurban, 2022). There will be a customer control center that keeps an eye on the roads to ensure travelers are moving, and if an incident happens, a responding crew will arrive with help in a short time.

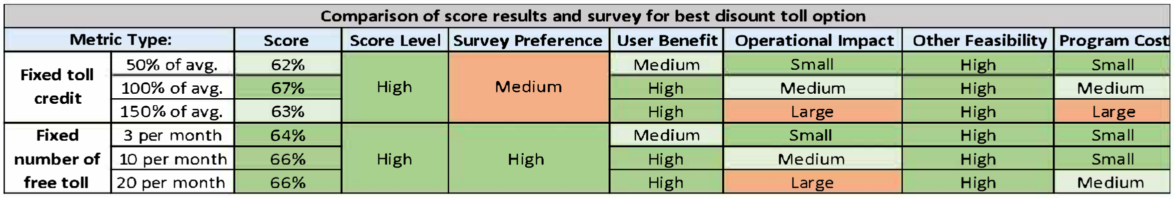
Carpools and vanpools in Virginia can travel toll-free on the Express Lanes at all times as long they fit within the free travel guidelines for Virginia. The Transurban has a partnership with the Virginia Department of Transportation to manage and operate the 495, 95, and 395 Express Lanes. Transurban stated that if the traveler has a headcount of 3 or more people in the carpool or vanpool, the drivers need to make sure that they switch the E-ZPass Flex to HOV mode to travel for free. Motorcycle riders can enjoy a toll-free trip on Express Lanes—even if they have the E-ZPass, and they will not be charged (Transurban (2022)). Virginia also welcomes buses of any size to use the Express Lanes for free. All they need is an E-ZPass. Law enforcement may travel the Express Lanes for free under different circumstances like responding to an emergency.

Taxi drivers are allowed to use the Express Lanes at any time with an E-ZPass or E-ZPass Flex to pay tolls. Express Lanes are tolled for 24 hours a day. Meanwhile, free travel is always available for motorcycle riders, and HOV-3+ vehicles with an E-ZPass Flex set to HOV mode (Transurban (2022)). Toll price changes are often based on the dynamic pricing system that was established. Usually, heavy congestion, or events that cause traffic congestion, like accidents or lane closures, can raise rates a little higher than usual. Dynamic pricing can be changed based on real-time traffic conditions. Sensors can be placed alongside the road to monitor traffic levels and speed. Depending on the flow of the roads and cars, toll prices will go up or down accordingly. Travelers can determine the toll rates before their travel using the Express Lanes Mobile App.

The Department of State Health Services (DSHS) and King County Metro noted that even discounted toll charges could be a barrier to low-income users. DSHS and King County Metro are expecting more uptake for a program that offers some free travel. The Washington

State Transportation Center noted in their Study on “I-405 Express Toll Lanes: Usage, Benefits, and Equity,” that users with high income use the facility more often but do not make up the majority of users. Low-income drivers benefit more per trip, while high-income users benefit more in general (Debreczeni, 2021).

Observed experience from existing programs and Express Toll Lanes (ETL) corridors in CA, GA, VA, and TX that there would be very limited enrollment if rewards were low. Cash transactions would be beneficial for low-income users, and requiring account balances and automatic reloading can be an issue for low-income users (Debreczeni, 2021). The comparison of score and survey results for different discount toll options indicates that **fixed toll credit and fixed number of free toll trips** have the highest score level and users benefit with an average of small and medium program cost (Debreczeni, 2021) as shown in Figure 2.



Comparison of score results and survey for best disount toll option

Metric Type:		Score	Score Level	Survey Preference	User Benefit	Operational Impact	Other Feasibility	Program Cost
Fixed toll credit	50% of avg.	62%	High	Medium	Medium	Small	High	Small
	100% of avg.	67%			High	Medium	High	Medium
	150% of avg.	63%			High	Large	High	Large
Fixed number of free toll	3 per month	64%	High	High	Medium	Small	High	Small
	10 per month	66%			High	Medium	High	Small
	20 per month	66%			High	Large	High	Medium

Figure 2 Discount options that received highest score ratings based on user surveys (Debreczeni, 2021)

The most preferred option in the survey is 10 free ETL trips per month. The program would encourage the use of ETLs for infrequent high-value trips such as medical, children, and late work. The highest scoring option via the scoring metric is a toll credit equal to the tolls paid by the average ETL user (~$50/month).

Standard Program Components:

- Provide free good-to-go pass to pay the lowest toll rate for the program users.
- The program has an advisory panel that is diverse with regard to gender, race, age, and geography of residence.
- The program documentation to be in all primary languages, with available translation for other languages that are used in the region.
- The program information is preferred to be in visual formats.
- Enrollment process (physical and remote) should count for users with disabilities.
- Physical program enrollment location should be in an accessible location.

A recent study evaluated the available tolling program for low-income groups and how it works by studying various Express Lanes in the United States. The study focuses on defining any existing proposed toll discount and/or credit program for drivers with low income and how to improve that. This study recognized one toll discount program in Virginia that provides a fixed discount of 75 cents per trip after making eight trips per month (WSP USA, 2021). Another program in the Los Angeles area is offering a one-time toll credit of $25 including a waiver of a monthly $1 administrative fee. In Minnesota, a program that offers annual toll credits to low-income drivers was proposed in 2017 but awaits authorization to implement (WSP USA, 2021).

There was also a minimum of four tolling programs in the United States that have included low-income toll discounts in the planning stages of the Express Lanes (WSP USA, 2021).

- Two Express Lanes in the San Francisco Bay area where they are providing a percentage discount per trip.
- One in Colorado with not yet of program elements.
- One in the San Bernardino area where they provide discounts for enrollment and other non-toll rate discount.

The result of this research has recognized more than 20 potential low-income tolling discount options that are available for users (WSP USA, 2021). This gives a clear vision on knowing how these discount toll rates are assigned for low-income drivers to ensure providing equitable toll rates.

These selected program options have the highest scores on the metric and survey as well of residents with low incomes (WSP USA, 2021). These programs focused on user benefits including benefits to drivers of infrequent but high-value trips.

- **Fixed Number of Free Toll Trips**: This program participant receives ten free ETL toll trips per month for users.
- **Fixed Toll Credits**: This program participant receives a monthly toll credit that equals 100% of the average ETL customer –assessed at $48 monthly in toll credits.

Taking into consideration the results of this research, some recommendations arrived at support the future implementation of low-income tolling programs. These are the eight recommendations that can be used to advance further development of the low-income discount program:

- **Recommendation 1:** Consider developing a clear concept of operations for the low-income toll discount program.
- **Recommendation 2:** Demonstrate an implementation timeline that supports informed program selection and cost-effective approaches.
- **Recommendation 3:** Consider and advance the two selected program options, fixed number of free toll trips and fixed toll credit, as preferred options for further development.
- **Recommendation 4:** Attract potential program participants to inform the program design process.
- **Recommendation 5:** Apply a low-income toll discount program as a pilot initially, to try out and develop further guidance.
- **Recommendation 6:** Utilize existing programs to support cost-effective program enrollment.
- **Recommendation 7:** Establish stable program elements that support and allow participant access.
- **Recommendation 8:** Evaluate costs and benefits of expanding to all tolled facilities.

In this report, we integrate these recommendations by evaluating equity from a modeling perspective.

APPROACH AND METHODOLOGY

This section outlines the modeling approach to quantifying and addressing equity gaps between groups. We consider a mesoscopic cell-transmission based traffic flow model with a trapezoidal fundamental diagram which ignores the impacts of lane changes. Furthermore, we assume that travelers do not equilibrate their route or time of departure. In this study, we conduct a simulation-based analysis of dynamic tolls.

Equity Evaluation Framework

Considering the five-step equity analysis framework in Figure 1(a), we first determine the relevant factors for equity analysis:

- **Population for Analysis**: We consider the population of travelers who wish to travel from an origin to a destination using their personal vehicle. These travelers can be further grouped based on their need for travel. The primary criterion used for grouping is the value of travel time (VOT) defined as the dollar amount value that an individual is willing to sacrifice in order to save a unit of travel time. We measure VOT in $/hr. It has been shown that VOT is correlated with an individual's income.
- **Needs and concerns**: Transportation systems connect individuals to their destination. We consider that the primary need of a traveler is to arrive at their destination as quickly as possible by minimizing the travel time they incur while driving on the roadway system. Given this need, an equity concern emerges when certain groups of travelers are forced to spend extra time on travel relative to other groups. As we demonstrate later, the travel time spent by low VOT travelers is commonly higher and if VOT correlates with travelers' income, then low-income travelers suffer a higher burden of congestion relative to high-income travelers. It is worth noting that transportation is one of the basic needs of travelers and is not a luxury item that only individuals with a high willingness to pay need to access.
- **Measuring impacts of proposed options**: Express lanes charge tolls, and we measure how these lanes create equity differences by considering a modeling perspective described later in this section. Broadly, we consider the interaction between supply and demand side models for travelers using the corridor.
- **Determine disparities**: In our analysis, disparities are measured by quantifying the average delay per person experienced by a traveler in each VOT group and using the maximum absolute difference of delay differential as the equity metric. We choose this metric since the purpose of managed lanes is to provide reliable travel time. This equity metric is defined later in terms of the modeling parameters.

- **Develop strategies to mitigate inequities**: Once we quantify equity, we determine strategies that can address this gap. In particular, we consider various discounting methods for travelers in different VOT groups.

Component Models

Broadly, component models for express lanes can be categorized as shown in Figure 3 below. We discuss these component models next.

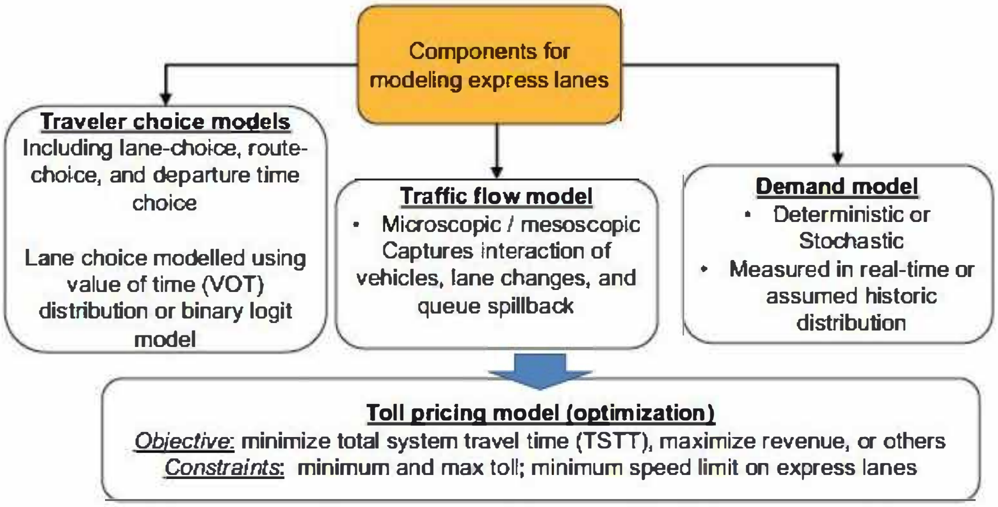


Figure 3: Component models for express lanes

Consider a managed lane network in Figure 4 given by a directed graph $G = (N, A, Z)$ where N is the set of all nodes, A is the set of all links, and Z is the set of all zones where trips begin or end. Let $\mathcal{T}$ be the set of toll gantries where tolls are collected. We assume that these gantries are located on links. Let $A_{\mathcal{T}} \subset A$ be the subset of links that charge a dynamic toll. Without loss of generality, the tolled links are selected such that the tail node of the links is a diverge node where travelers make a choice between express lane and general-purpose lanes. Assessing the impacts of various congestion pricing metrics is done by integrating models for interactions between transportation demand and supply, which we define next.

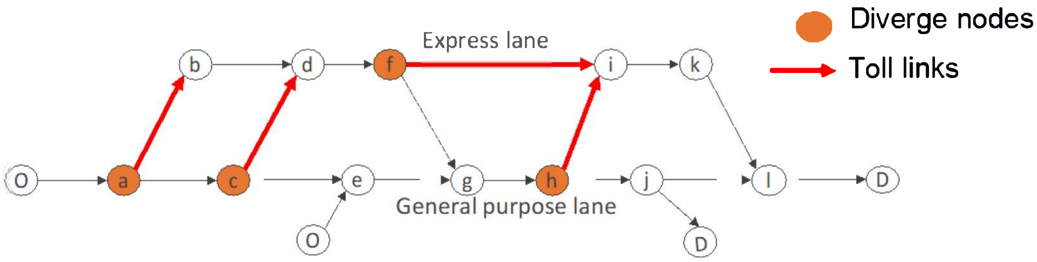


Figure 4: An express lane network comprising of links that are part of express lanes and general-purpose lanes. Toll gantries are assumed to be located on highlighted toll links. Travelers enter the corridor through origin nodes and exit through destination nodes

Demand characteristics: We consider deterministic time-dependent demand using the corridor between an origin-destination pair. Let $d_{rs}(t)$ be the demand entering the corridor at time t at origin node $r \in Z$ traveling towards destination $s \in Z$. For simplicity of the model, we assume that travelers do not adapt their departure time in response to tolls and thus $d_{rs}(t)$ is assumed known apriori (estimated using the historical usage of the tolled facility). We group the travelers by their value of time (VOT) modeled using a discrete VOT distribution. Let α_k represent the VOT for travelers in group $k \in K$ where K is the set of all groups. Without loss of generality, we order travelers such that $\alpha_1 > \alpha_2 > \cdots > \alpha_{|K|}$e As discussed earlier, such distributions can be estimated using historical travel patterns based on the income distribution for travelers using the corridor.

Traffic flow model (Supply-side characteristics): Models for traffic flow determine the variation of traffic density for different times and locations expressed as a partial differential equation. The Lighthill-Whitham-Richards (LWR) assumes a deterministic relationship between density and flow expressed as the fundamental diagram. In our analysis, we model the evolution of traffic on the corridor using a macroscopic multiclass cell transmission model (Daganzo, 1995) which numerically solves the LWR equation by dividing the space into cells and time into discrete time-intervals (let T be the set of all time intervals). The multiclass CTM model relates flow and density on each link using a trapezoidal fundamental diagram. For brevity, we refer the reader to prior literature on multiclass CTM model for further details (Tan and Gao, 2018; Pandey and Boyles, 2018).

Lane choice model: At each diverge point, a traveler from a VOT group $k \in K$ compares the utility across different lane alternatives. Utility of travelers making a decision at toll gantry $g \in \mathcal{T}$ is determined as a linear combination of travel time and toll on managed lane and GPL options. We assume that the information about the current travel time is provided by measuring instantaneous travel time with no time lag, and that all travelers' utility are calculated only using the instantaneous travel time and toll information. For a given diverge point, we consider two routes connecting the current diverge with the first exit from the managed lane if a traveler were to enter the managed lane then. For example, in Figure 4, the routes considered at diverge node a are $[a, b, d, f, g]$ and $[a, c, e, g]$. The utility on a route for a traveler in group $k \in K$ is then given as the linear combination of travel time and toll: $U = \alpha_k t + \tau$ where t and τ are travel times and tolls for the route.

Toll Optimization using Reinforcement Learning

Once the interaction between supply and demand is established, the toll optimization problem can be formulated as the choice of toll $\tau_{ML}^{l}(t)$ for toll link $l \in A_{\mathcal{T}}$ at different time intervals $t \in T_{toll} \subset T$ (since tolls are updated less frequently than traffic updates). We consider two objectives for toll optimization: maximizing revenue and minimizing total system travel time (TSTT).

Building on the open-source reinforcement learning framework in Pandey et al. (2020), we optimize the toll using a reinforcement learning framework. The components of the Markov decision process associated with the reinforcement learning problem are outlined below:

- **Timestep**: Tolls are optimized over a finite time horizon for each time interval $t \in T_{toll}$.
- **State**: The traffic state at any given time is characterized by number of vehicles of each group $k \in K$ across all cells in the network.

- **Action**: The action in any state is the toll charged on each toll links $l \in A_T$, where the toll is considered bounded $\tau_{ML}^{l}(t) \in (\tau_{min}, \tau_{max})$
- **Transition function**: The transition from a given state and the chosen action is governed by the multiclass cell transmission model
- **Reward**: The reward in each state after taking an action is governed by the tolling objective. For revenue maximization, the reward is the immediate revenue obtained in that time-step. For TSTT minimization, the reward is the equal to the total number of vehicles present in the network multiplied by minus 1 (to accommodate the minimization objective).

For the experiments, we use the OpenAI-gym RL environment for macroscopic simulation provided by Pandey et al. (2020) and use the open-source implementation of the Soft-Actor Critic algorithm (Hou et al., 2020) to find tolls that maximize the reward over the time horizon. The SAC algorithm has been shown to converge to optimal tolls for the express lane pricing problem (Pandey et al., 2020) and in our experiments, we observe the same pattern of convergence. To keep the focus on equity issues, we only report the performance of optimal tolls obtained at the termination of the SAC algorithm as discussed next.

FINDINGS AND RESULTS

We conduct our analysis on the network for toll segment 2 of the LBJ TEXpress lanes in Dallas, TX provided in the literature with demand and network files available online (Pandey et al., 2020). The demand is simulated for a two-hour period. First, we conduct an analysis for five VOT groups with values and proportion in the population as follows: $\frac{\$10}{hr} \rightarrow 10\%, \frac{\$15}{hr} \rightarrow 40\%, \frac{\$20}{hr} \rightarrow 20\%, \frac{\$25}{hr} \rightarrow 20\%, \$$ and $\frac{\$30}{hr} \rightarrow 10\%$.

If total corridor demand at a given time is greater than the bottleneck capacity, then there will be inevitable congestion. However, due to toll choices, the total corridor capacity may be underutilized resulting in additional congestion. Jam-and-harvest is an unintentional characteristic of tolls that create more "jam" on general-purpose lanes by charging a high toll, resulting in "harvesting" more revenue (Pandey et al., 2020). Time-space diagrams of revenue-maximizing toll profiles show that when maximizing revenue, the express lane capacity is underutilized (Figures 5 and 6). In contrast, the tolls profiles that minimize TSTT allow for appropriate utilization of corridor capacity, and thus the curve for the cumulative number of exited vehicles has a sharper slope for tolls minimizing TSTT relative to tolls that maximize revenue (Figure 6).

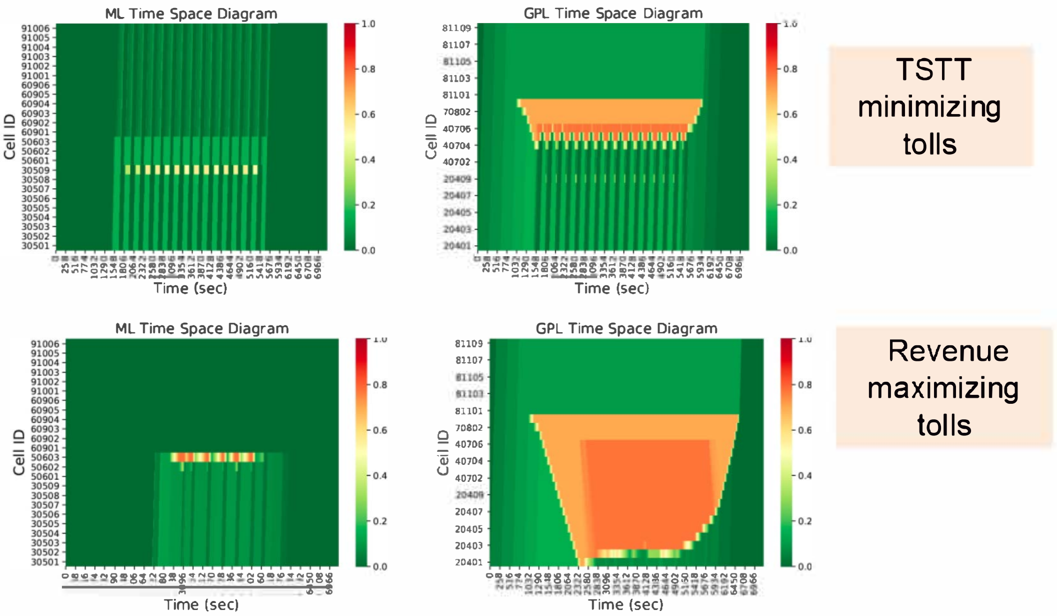


Figure 5: Time-space diagrams showing the ratio of traffic density to maximum density across the corridor for revenue-maximizing tolls. As observed, tolls maximizing the revenue create additional congestion on general purpose lanes (GPL) relative to managed lanes (ML) (Pandey et al., 2020)

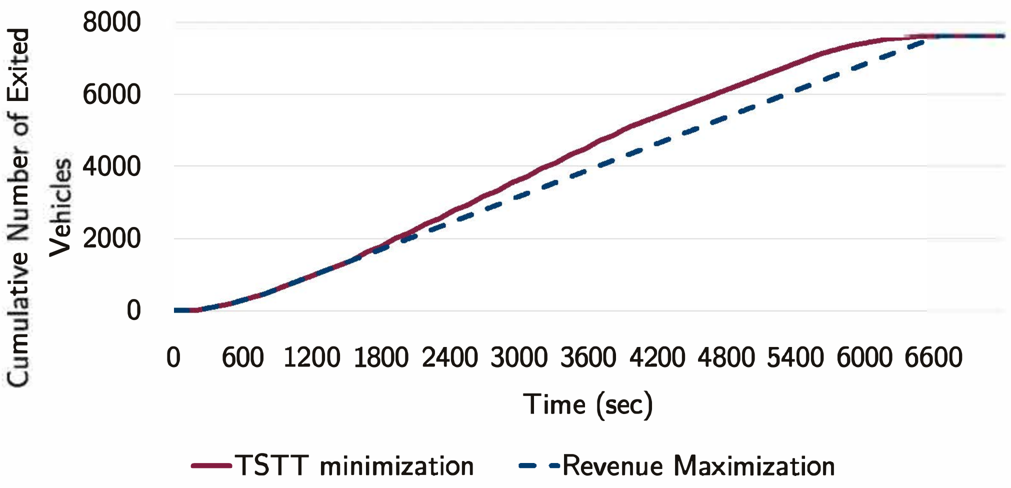


Figure 6 : Cumulative number of exited vehicles through the corridor for optimal tolls corresponding to TSTT minimization and revenue maximization objectives.

Next, we analyze the differential of delays observed by travelers across different groups. We define delay differential (Δ_τ) as the absolute range of average delay per vehicle for travelers across different VOT groups for a given toll profile $\boldsymbol{\tau}$. That is,

$$\Delta_\tau = \max_{k \in K} \frac{TSTT_k}{D_k} - \min_{k \in K} \frac{TSTT_k}{D_k}$$

where $TSTT_k$ is the total system travel time and D_k is the total demand for travelers in group $k \in K$. The ratio $\frac{TSTT_k}{D_k}$ represents the average delay per vehicle for group .

Simulation-based Evaluation

We conducted simulation-based evaluation of tolls for express lanes. First, we sample various toll profiles in a systematically random manner using the following algorithm for generating toll profiles:

Step 1: For every toll-gantry, we first consider a constant toll setting where the toll can either be set to the maximum or minimum value. With $\mathcal{T}$ as the set of all toll gantries, we obtain $2^{|\mathcal{T}|}$ toll profiles. These toll profiles enable us to consider valid extreme scenarios useful for benchmark comparisons.

Step 2: Sample N profiles randomly (N=5000 for our experiments)

```
for profile id ∈ {1,2,....N} do
    for time index t ∈ {1,2 ... $T_{toll}$} do
        if rem(N,10) equals 0 or 4
        for each toll gantry g ∈ $\mathcal{T}$
            set toll $\tau_g^N(t)$ randomly in the range $(\tau_{min}, \tau_{max})$
        else if rem(N,10) equals 1, 5, or 8
        for each toll gantry g ∈ $\mathcal{T}$
            set $\tau_g^N(t)$ randomly in the range
                $(\tau_g^N(t-1) - 0.25, \tau_g^N(t-1) + 0.25)$
        else if rem(N,10) equals 1, 5, or 8
        for each toll gantry g ∈ $\mathcal{T}$
            set $\tau_g^N(t)$ randomly in the range
                $(\tau_g^N(t-1) - 0.75, \tau_g^N(t-1) + 0.75)$
    else
        for each toll gantry g ∈ $\mathcal{T}$
            set $\tau_g^N(t)$ the same value as $\tau_g^N(t-1)$
        end if
    end for
end for
```

<u>Step 3</u>: Simulate all random toll profiles using the set traffic flow model

Figure 7 shows the variation of TSTT and revenue for 5000 different toll profiles, where similar to the observations in the literature a high revenue profile showed high TSTT value resulting in higher average delay per group. Figure 8 shows the variation of $\frac{TSTT_k}{D_k}$ for all travel groups for the toll profiles obtained on the Pareto-frontier of TSTT vs revenue plot. We observe that toll profiles that exhibit higher "jam-and-harvest" create differential delays across population groups where travelers with the lowest value of time suffer the highest delay. The delay differential for revenue maximizing profile was found to be 5.95 minutes while for TSTT minimizing profile was 1.68 minutes. **This additional congestion burden falls on travelers with a lower VOT, which correlates with lower income levels.**

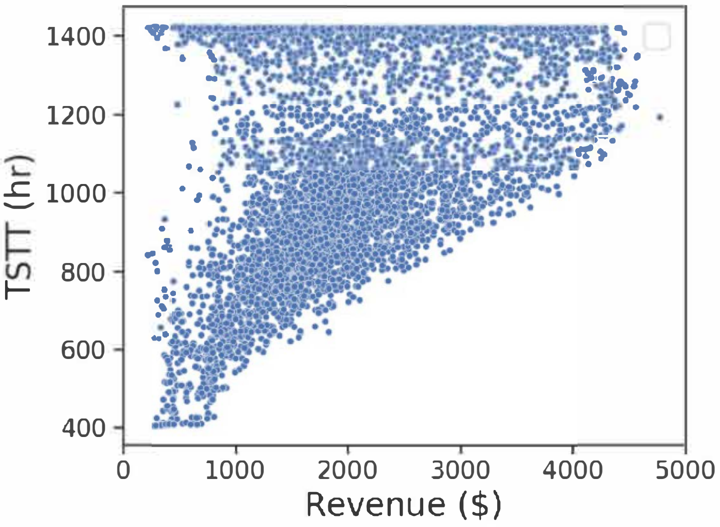


Figure 7: Sampled toll profiles positioned in the space of TSTT and revenue

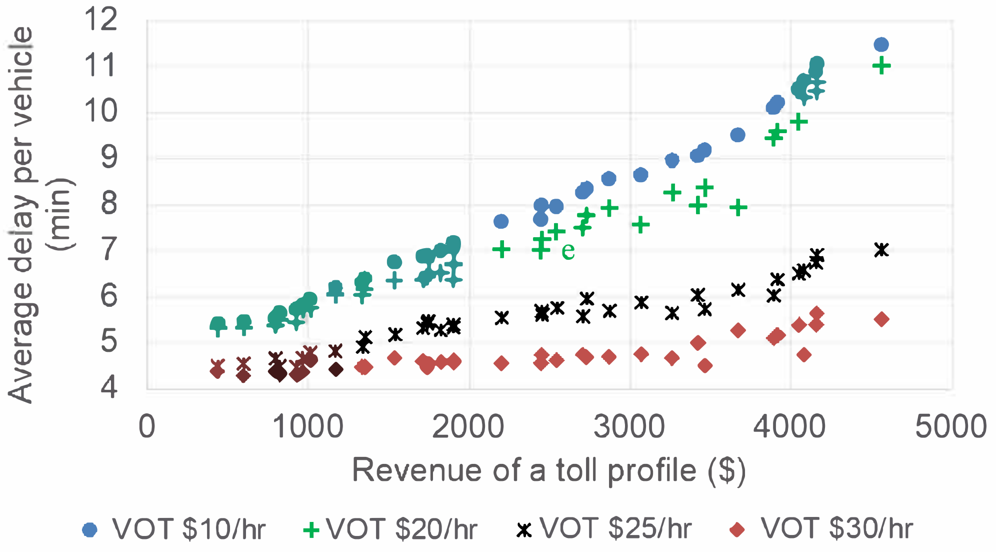


Figure 8: The delay difference across travelers with values of time (VOT) $10/hr and $30/hr is higher for revenue maximizing tolls

Next, we analyzed the impact of different factors affecting the delay differential. We made the following observations:

If demand diversion is ignored, delay differentials are higher for higher demand values: For revenue-maximizing tolls under high demand, low VOT travelers spend an average of 13.3 minutes higher than the high VOT travelers (an increase of six minutes relative to when the demand is at the base level). The plot of delay differentials across the Pareto-Frontier is shown below.

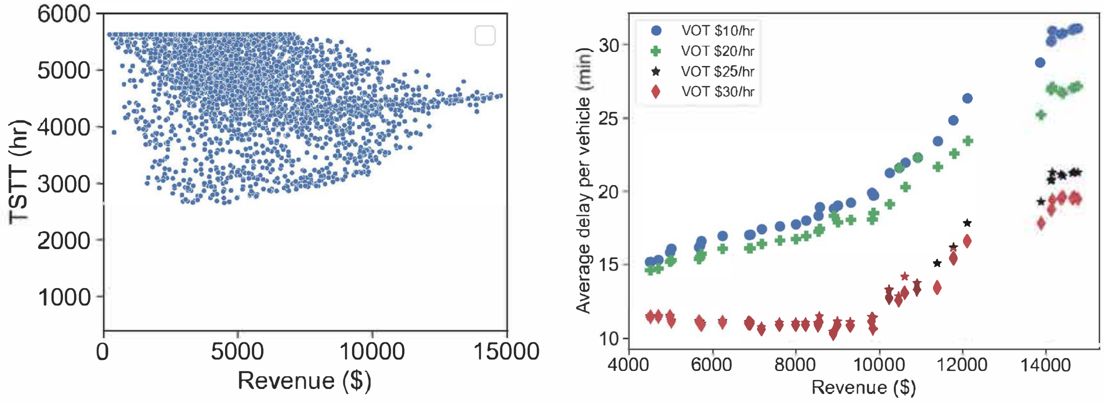


Figure 9: (a) TSTT vs Revenue for the sampled toll profiles and (b) delay differentials for toll profiles on the Pareto Frontier in the case where demand is 1.5 times higher than the base demand with no demand-diversion

Increasing the toll upper limit from \$4 to \$8 increases the delay differential: If the toll upper limit is increased, there is a higher potential for increased revenue generation. We observe a 10% increase in maximum revenue relative to \$4 max tolls. The delay differential increases by approximately one minute (~16%) for the base demand.

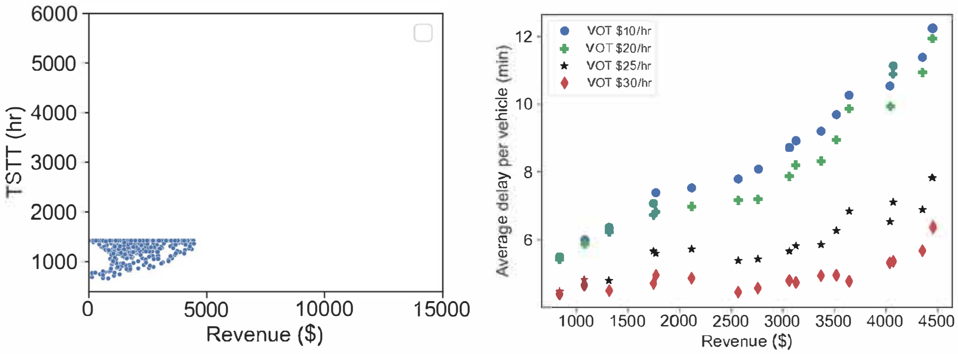


Figure 10: (a) TSTT vs Revenue for the sampled toll profiles and (b) delay differentials for toll profiles on the Pareto Frontier in the case where maximum tolls are increased from \$4 to \$8.

Incorporating demand diversion due to alternate routes lowers the delay differential: If the demand is diverted due to the presence of alternate routes, then the impact of jam-and-harvest is lowered, and the delay differential drops by five minutes (~83% reduction) relative to the case when no alternate routes are present.

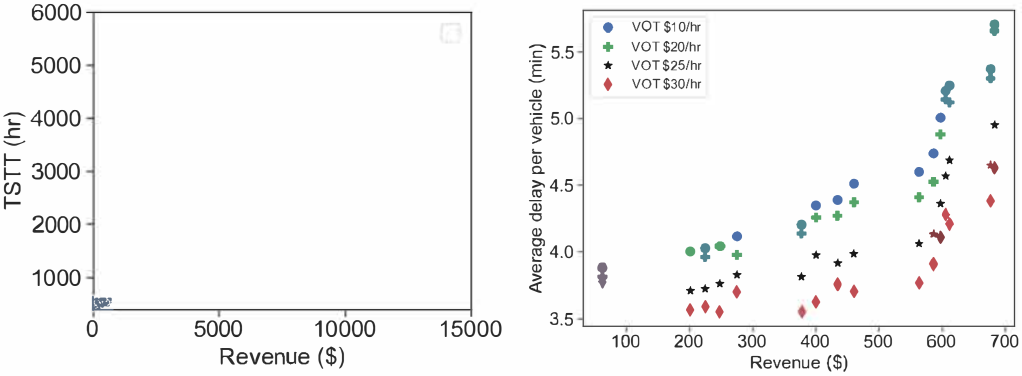


Figure 11: (a) TSTT vs Revenue for the sampled toll profiles and (b) delay differentials for toll profiles on the Pareto Frontier in the case where demand is 75% of the base demand due to demand-diversion

If lane choice is stochastic and depends on factors others than toll and travel time, then the delay differentials are lower: When lane choice is stochastic (governed by the Logit model), then travelers are likely to choose toll roads even when travel time savings are negligible. Under this scenario, minimizing TSTT reduces the differential of delay across groups to zero; while maximizing revenue reduces the delay differential by approximately one minute (~15% reduction).

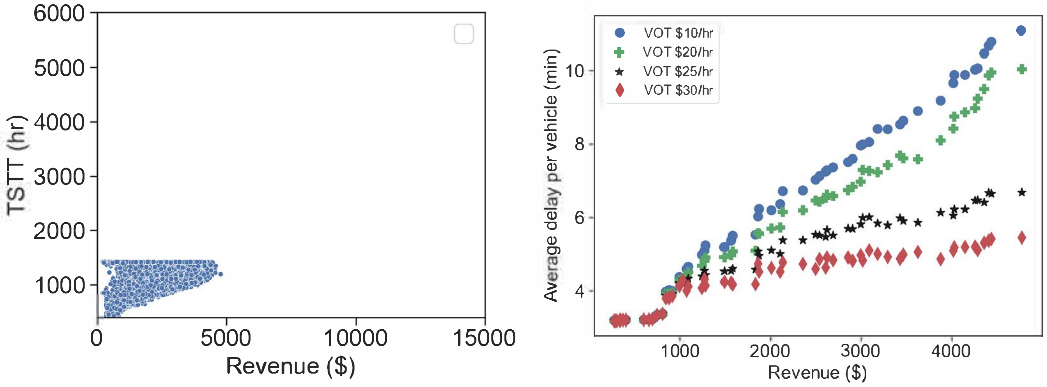


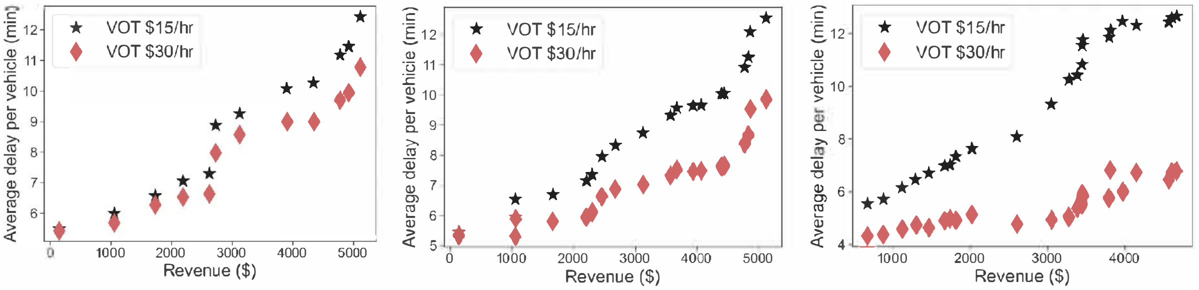
Figure 12: (a) TSTT vs Revenue for the sampled toll profiles and (b) delay differentials for toll profiles on the Pareto Frontier in the case where lane choice is governed by the stochastic Logit model than the deterministic VOT-based model

The summary of these influencing factors on the delay differential is highlighted in the table below.

Table 1: Variation of delay differential for changes in toll upper bound and demand proportion

		Δ_τ Revenue Maximization tolls (minutes)	Δ_τ TSTT Minimization tolls (minutes)
Changing toll upper bound	Toll range (0.1,4)	5.95	1.68
	Toll range (0.1,8)	6.52	1.98
Proportion of base demand	Base demand (100%)	5.95	1.68
	Reduced demand due to diversion (75%)	1.5	0.24
	Increased demand due to increasing corridor attractiveness (125%)	11.24	4.91

We also analyzed the impact of changing the proportion of travelers within each group. For this analysis, we modify the value of time distribution to consider two VOT groups: $15/hr and $30/hr, and analyze the delay differential for varying proportions of travelers in each group. Figure 13 shows the average delay per vehicle for the two groups for varying proportions of travelers. As observed, higher the proportion of lower VOT travelers, higher is the delay differential. In absolute terms the delay for higher VOT travelers decreases as the proportion of lower VOT travelers increases; this is because, the delay for lower VOT travelers remains fixed due to the bottleneck on GPLs, while higher VOT travelers are able to reduce their travel time by efficiently utilizing the managed lane.



$15/hr: 25% of population
$30/hr: 75% of population

$15/hr: 50% of population
$30/hr: 50% of population

$15/hr: 75% of population
$30/hr: 25% of population

Figure 13: The plot of average delay per vehicle for the two groups for varying proportion of low VOT travelers on the Delay-Revenue pareto frontier

While we observe that certain choices of tolls can reduce the delay differential, there is no choice that can eliminate it completely. In the next section, we argue for the design of differential tolls to ensure equitable delay across groups.

Design of Equitable Discounts

In this section, we discuss the design of discounts differentiated by travelers' VOT. We analyze the choice of discounts for deterministic and stochastic lane choices while focusing on two VOT groups (though the results can be generalized for multiple groups).

First, we analyze the factors influencing the selection of different options assuming deterministic lane choices. For a given toll gantry $g \in \mathcal{T}$, let Δt_g be the travel time savings obtained on choosing the ML option and τ_{ML}^{g} be the toll to be paid. A traveler in group k with VOT α_k will choose ML if $\alpha_k \Delta t_g$ is greater than τ_{ML}^{g}. Arranging the groups by increasing the order of VOT and considering two groups, Figure 14 shows the region in the space of $(\Delta t_g, \tau_{ML}^{g})$ where a traveler chooses managed lane. As expected, travelers in group 1 have a larger region where they are likely to choose ML simply because they have a higher value of time.

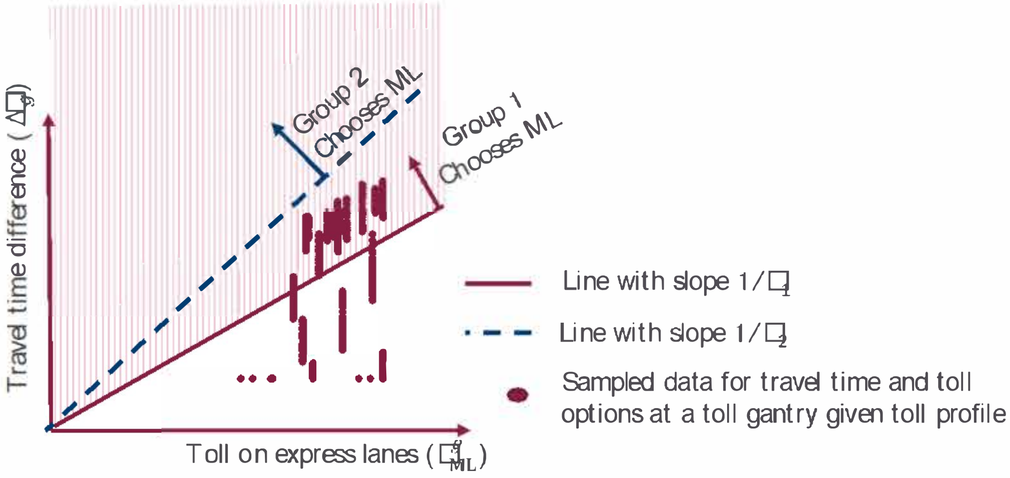


Figure 14: Region in the $(\Delta t_g, \tau_{ML}^g)$ space where travelers with two groups choose ML considering deterministic lane choice.

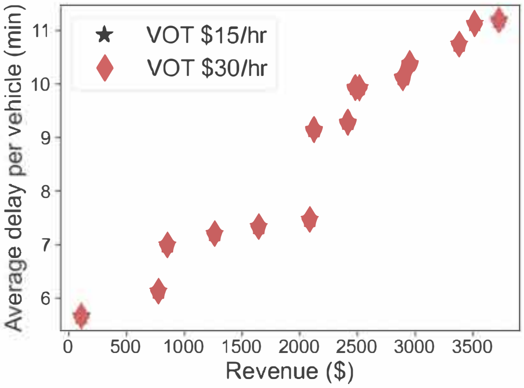
Figure 14 also shows the scatter plot of sampled data on travel time difference and toll on express lane observed on the first toll gantry on LBJ TEXpress lanes for revenue-maximizing tolls (shown as red dots). As observed, the realized values in the $(\Delta t_g, \tau_{ML}^g)$ space only correspond to tolls that allow travelers in group 1 to choose ML, and travelers in group 2 can never access ML for the set value of tolls (which are too high for their range).

Hence, we argue that by simply setting the discounts in proportion to travelers' VOT, the delay differentials across the groups are equitable. In particular, if we assume that the traveler with the highest VOT receives no discount, then the following proposition establishes the discount for other VOTs.

Proposition 1: *Considering deterministic lane choice, if we offer a traveler in group $k \in K$ the following discount (z_k) then all travelers enjoy equitable benefits.*

$$z_k = \left(1 - \frac{\alpha_k}{\alpha_1}\right) \times 100\%$$

Proof: The proof is based on Figure 14 where if the selected discount is applied and the traveler in group k pays the toll $(1 - z_k)\tau_{ML}^g$, then the region for choosing ML is identical for each traveler and delay differentials are identical. For our experimental analysis, we can verify that by offering a discount of 50% to travelers in VOT \$15/hr, the delay differentials are zero (Figure 15). **Hence proved**.



50% discount for $15/hr

Figure 15: Equitable discount for the two traveler case considering deterministic lane choice

However, the above proposition doesn't generalize for stochastic lane choices where each traveler may have a different probability of choosing ML in the $\left(\Delta \mathrm{t}_{\mathrm{g}}, \tau_{\mathrm{ML}}^{\mathrm{g}}\right)$ space depending on their VOT value. In this case, the design of discounts depends on the value of tolls and travel time at each gantry as discussed next.

Proposition 2: *For a general lane choice model, the optimal discount* z_k *decreases linearly with the VOT of travelers.*

Proof:

An equitable toll policy is one that provides equal opportunities for all groups of travelers to save time by choosing the managed lane. Hence, probability that a traveler chooses a managed lane must be independent across all groups. That is,

$$\mathbb{P}_{\mathrm{ML}}(\alpha_1) = \mathbb{P}_{\mathrm{ML}}(\alpha_2) = \cdots = \mathbb{P}_{\mathrm{ML}}\left(\alpha_{|K|}\right).$$

For a given travel group $k \in K$ which is offered a discount of z_k, the actual toll paid is $(1 - z_k)\tau_{ML} = \zeta_k \, \tau_{ML}$ where τ_{ML} is the current toll rate.

$$\begin{aligned} \mathbb{P}_{\mathrm{ML}}(\alpha_k) &= \mathbb{P}(U_{\mathrm{ML}} > U_{\mathrm{GPL}}) \\ &= \mathbb{P}(-t_{\mathrm{ML}}\alpha_k - \zeta_k\tau_{\mathrm{ML}} + \epsilon_{\mathrm{ML}} > -t_{\mathrm{GPL}}\alpha_k + \epsilon_{\mathrm{GPL}}) \\ &= \mathbb{P}(\Delta t\alpha_k - \zeta_k\tau_{\mathrm{ML}} > \epsilon_{\mathrm{GPL}} - \epsilon_{\mathrm{ML}}) \end{aligned}$$

Since the distribution of the errors for all utilities are independent and identically distributed (IID), the probabilities of choosing managed lanes are identical only if the term $\Delta t \; \alpha_k \; - (1 - \zeta_k)\tau_{ML}$ is identical for groups. Equating the terms for two groups $k_1, k_2 \in \; K$:

$$\begin{aligned}\Delta t\alpha_{k_1} - (\zeta_{k_1})\tau_{\text{ML}} &= \Delta t\alpha_{k_2} - (\zeta_{k_2})\tau_{\text{ML}} \\ \Rightarrow \frac{\alpha_{k_1} - \alpha_{k_2}}{\zeta_{k_1} - \zeta_{k_2}} &= \frac{\tau_{\text{ML}}}{\Delta t}\end{aligned}$$

where the RHS expression is constant across all groups for a given toll gantry at a given time. Let groups be indexed $\{1,2,\dots,|K|\}$ such that $\alpha_1 \geq \alpha_2 \geq \cdots \geq \alpha_{|K|}$. Allowing this calculation for all groups relative to group 1, we obtain:

$$\frac{\alpha_1 - \alpha_2}{\zeta_1 - \zeta_2} = \frac{\alpha_1 - \alpha_3}{\zeta_1 - \zeta_3} = \cdots$$

This implies that on the curve (α, ζ) for different groups, the slope of line connecting the point for group $k \in \{2, \dots |K|\}$ to group 1, given by $(\zeta_1 - \zeta_2)/(\alpha_1 - \alpha_2)$, is identical across groups. If we allow the traveler with the highest VOT to get zero discount, that is $\zeta_1 = 1$, then ζ_k for any group $k \in \{2, \dots |K|\}$ the discount decreases with the decreasing value of α_k for that group. That is, values of ζ_k (and thus z_k) are linear in the VOT of travelers. **Hence proved**.

From Proposition 2, we can deduce that for gantry $g \in \mathcal{T}$, the optimal discount offered to a traveler in a group k is given by z_k which is calculated as follows:

$$\begin{aligned}\frac{\zeta_1 - \zeta_k}{\alpha_1 - \alpha_k} &= \frac{\Delta t_g}{\tau^g_{\text{ML}}} \\ \zeta_k &= 1 - \frac{\Delta t_g}{\tau^g_{\text{ML}}}(\alpha_1 - \alpha_k) \\ z_k &= \frac{\Delta t_g}{\tau^g_{\text{ML}}}(\alpha_1 - \alpha_k)\end{aligned}$$

Proposition 2 holds true for all choice models regardless of the distributions of error terms in the utilities as long as they are IID. To allow the discounts to not be greater than 100%, we can set $z_k = \max\left\{1, \frac{\Delta t_g}{\tau^g_{\text{ML}}}(\alpha_1 - \alpha_k)\right\}$. Note that the obtained value of the optimal discount is dependent on the toll gantry as well as the current values of travel time differences and tolls. This may be difficult to implement in practice; however, it can be made possible through technologies such as phone apps or personalization of tolls achieved by toll tag observations.

Finally, we evaluate the tradeoffs in the loss of the system's efficiency defined across various metrics by providing equitable discounts. If we provide optimal discounts to travelers, the price of fairness (POF) is computed as the approximate loss of "system efficiency" to allow for fair outcomes. We can measure system efficiency in terms of loss of revenue or increase of total system delay computed as follows:

$$\mathrm{POF}_{\mathrm{revenue}} = \frac{\text{Loss of revenue for fair outcome}}{\text{Maximum revenue}}$$

$$\mathrm{POF}_{\mathrm{TSTT}} = \frac{\text{Increase in TSTT for fair outcome}}{\text{Minimum TSTT}}$$

In our experiments for LBJ TEXPress lanes for the provided VOT distribution with 5 groups, the values for $\mathrm{POF}_{\mathrm{revenue}}$ range from 0.25—0.34, whereas the values for $\mathrm{POF}_{\mathrm{TSTT}}$ range from 0-0.09. We observe that the revenue loss is more significant for the economically fair option; this result is as expected due to the inherent jam-and-harvest phenomenon observed with revenue maximizing tolls which no longer occurs if we allow travelers in both groups to use the managed lanes.

CONCLUSIONS, RECOMMENDATIONS, AND FUTURE WORK

Creating equitable access to transportation systems is the need of the hour. In this report, through simulation-based optimization of tolls using a RL framework, we argue that the choice of dynamic tolls impacts the delay differentials across different groups. We find that higher toll values and higher demand worsen the differentials. Furthermore, allowing demand diversion and considering alternative choice factors lower the differentials. We also proved that VOT-proportional discounts address equity differentials across delays. For the stochastic lane choice, the discounts are also a function of current toll and travel time savings at a given gantry. Furthermore, we demonstrate that equitable discounts may result in a 25% - 34% loss of revenue.

Recommendations: The research findings lead to the following recommendations:

1. First, it is recommended that equity considerations are explicitly incorporated as part of the dynamic tolling process. This requires measuring the differential distribution of equity measures across travel groups as outlined in Figure 1. In this study, the delay was considered as the equity measure, and future studies can extend this for other metrics.

2. Second, equitable discounts can be designed by considering the traveler's VOT distribution for a given express lane. Since the proposed discounts are a function of the traveler's VOT which is not a direct observable parameter, a few indirect and more acceptable alternatives can be chosen. These alternatives may use income as a proxy for the traveler's VOT. For example, on I-10 Express Lanes, low-income travelers receive $25 credit on transponders and monthly fees are waived. In addition, the VOT distribution can be estimated through revealed-preference surveys and analysis of toll data. Once estimated, the VOT distribution can be correlated with income levels and discounts can be offered based on the traveler's income group. The proposed discounts provide a stepping stone towards creating an equitable distribution of benefits across users of express lanes.
3. Finally, the quantification of the "price of fairness" suggests that there are tradeoffs associated with enforcing equitable discounts. The analysis of POF can enable transportation agencies to make effective decision on weighing equity relative to other priorities of the agency.

Being a simulation-based analysis, the study has a few limitations which can be addressed as part of future work. The following directions for future work have been identified. Analytical models incorporating departure-time choice (such as in Hall (2018)) can be analyzed for deriving upper and lower bounds on the price of fairness with respect to different objectives. Future studies can also conduct multi-objective analysis where we identify discounts that optimize the joint objective of maximizing revenue and minimizing equity using multi-objective reinforcement learning methods (Hayes et al., 2022). Similarly, future studies can replace the macroscopic traffic model with a microscopic model that captures the vehicle-to-vehicle interactions more closely, especially in areas where lane changes are prominent (such as near entrance and exit ramps for the express lanes). Finally, practical implementations of VOT-based discounts can be assessed using pilot programs for current managed lane projects across the world.

REFERENCES

A. Gordon, “The broken algorithm that poisoned american transportation.” 2021. URL: https://www.vice.com/en/article/v7gxy9/the-broken-algorithm-that-poisoned-american-transportation-v27n3. Last accessed: Aug, 2022.

AbuLibdeh, A. (2017). *Traffic Congestion Pricing: Methodologies and Equity Implication*(Rep.). IntechOpen. doi:10.5772/66569 https://www.intechopen.com/books/urban-transport-systems/traffic-congestion-pricing-methodologies-and-equity-implications

Aprahamian, H., Bish, D. R., & Bish, E. K. (2019). Optimal risk-based group testing. *Management Science*, *65*(9), 4365-4384.

Bender, E. A. (2000). *An introduction to mathematical modeling*. Courier Corporation.

Bertsimas, D., Farias, V. F., & Trichakis, N. (2011). The price of fairness. *Operations research*, *59*(1), 17-31.

Bills, T. S., & Walker, J. L. (2017). Looking beyond the mean for equity analysis: Examining distributional impacts of transportation improvements. *Transport Policy*, *54*, 61-69.

Daganzo, C. F. (1995). The cell transmission model, part II: network traffic. *Transportation Research Part B: Methodological*, *29*(2), 79-93.

Debreczeni (2021). Low-Income Toll Program Study for I-405 SR 167 Express Toll Lanes. URL: https://wstc.wa.gov/wp-content/uploads/2021/08/2021-WSTC-Tolling-Equity-Report.pdf. Last accessed: Aug, 2022.

Dempsey, P. S. (1990). The civil rights of the handicapped in transportation: The Americans with Disabilities Act and related legislation. *Transp. LJ*, *19*, 309.

Denninghaus, M. (2018). *How to Achieve a Fully Accessible Transport System in the EU*. European Transport and Mobility Forum. https://medium.com/@mobility4eu/how-to-achieve-a-fully-accessible-transport-system-in-the-eu-the-view-of-the-european-disability-649f55633790

E. Metro, "Low-income assistance plan," 2021. [Online]. URL: https://www.metroexpresslanes.net/offers-discounts/low-income-assistance/. Last accessed: Aug, 2022

Ecola, L., & Light, T. (2009). *Equity and Congestion Pricing* (pp. 1-38, Rep.). Santa Monica, CA: RAND Corporation. https://www.rand.org/content/dam/rand/pubs/technical_reports/2009/RAND_TR680.pdf

FHWA (2022). What is congestion pricing? URL: https://ops.fhwa.dot.gov/congestionpricing/cp_what_is.htm. Last accessed: Aug, 2022.

Giuliano, G. (1992). An assessment of the political acceptability of congestion pricing. *Transportation*, *19*(4), 335-358.

Gutjahr, W. J., & Fischer, S. (2018). Equity and deprivation costs in humanitarian logistics. *European Journal of Operational Research*, *270*(1), 185-197.

Hall, J. D. (2018). Pareto improvements from Lexus Lanes: The effects of pricing a portion of the lanes on congested highways. *Journal of Public Economics*, *158*, 113-125.

Hayes, C. F., Rădulescu, R., Bargiacchi, E., Källström, J., Macfarlane, M., Reymond, M., ... & Roijers, D. M. (2022). A practical guide to multi-objective reinforcement learning and planning. *Autonomous Agents and Multi-Agent Systems, 36(1)*, 1-59.

Helsel, J. W., Pandey, V., & Boyles, S. D. (2020). Time-Equitable Dynamic Tolling Scheme For Single Bottlenecks. *arXiv preprint arXiv:2007.07091.*

Hershey, C. L., Clark, S., Day, J. R., & Thatcher, R. H. (2010). Accessible public transportation in the United States: Twenty years after passage of the ADA. In *TRANSED 2010: 12th International Conference on Mobility and Transport for Elderly and Disabled PersonsHong Kong Society for RehabilitationS K Yee Medical FoundationTransportation Research Board.*

Hoe, N., & Kaloustian, T. (2014). Bike sharing in low-income communities: An analysis of focus groups findings fall 2014. *Institute for Survey Research: Temple University, December, 3*.

Hou, Z., Zhang, K., Wan, Y., Li, D., Fu, C., & Yu, H. (2020). Off-policy maximum entropy reinforcement learning: Soft actor-critic with advantage weighted mixture policy (sac-awmp). *arXiv preprint arXiv:2002.02829*.

Lazo, L. (2018). Virginia to tweak 66 Express Lanes pricing to address tolls that have topped $47. URL: https://www.washingtonpost.com/local/trafficandcommuting/virginia-to-tweak-66-express-lanes-pricing-to-address-tolls-that-have-topped-47/2018/04/30/70441ab8-4c88-11e8-84a0-458a1aa9ac0a_story.html (Last accessed Aug, 2022)

Litman, T. (2021). *Evaluating Transportation Equity*. Victoria Transport Policy Institute. https://www.vtpi.org/equity.pdf

Lombardi, C., Picado-Santos, L., & Annaswamy, A. M. (2021). Model-based dynamic toll pricing: An overview. *Applied Sciences*, *11*(11), 4778.

Madi, M., Wiegmann, J., & Parkany, E. (2013). *Guidebook for State, Regional, and Local Governments on Addressing Potential Equity Impacts of Road Pricing* (pp. 11-36). United States Department of Transportation. https://ops.fhwa.dot.gov/publications/fhwahop13033/fhwahop13033.pdf

n.a. (2020a). Managed Lanes Project Database. URL: https://managedlanes.wordpress.com/category/projects/e Last accessed: Aug, 2022

n.a. (2020b). I-77 Express Lanes FQAs. URL: https://www.i77express.com/using-the-lanes/faqs/. Last accessed: Aug, 2022

Nagatani, T. (2022). Dynamic transition induced by route choice in two-route traffic network with onramp. *Physica A: Statistical Mechanics and its Applications*, *596*, 127219.

NCHRP (2016). Introducing the NCHRP 15-49 implementation guide: Guidelines for Implementing Managed Lanes. *In 15th International Conference on Managed Lanes, number S-13*.

Pandey, V., & Boyles, S. D. (2018). Dynamic pricing for managed lanes with multiple entrances and exits. *Transportation Research Part C: Emerging Technologies*, *96*, 304-320.

Pandey, V., Wang, E., & Boyles, S. D. (2020). Deep reinforcement learning algorithm for dynamic pricing of express lanes with multiple access locations. *Transportation Research Part C: Emerging Technologies*, *119*, 102715.

Pathak, R., Wyczalkowski, C. K., & Huang, X. (2017). Public transit access and the changing spatial distribution of poverty. *Regional Science and Urban Economics*, *66*, 198-212.

Patterson, T., and Levinson, D. M. (2008). Lexus lanes or Corolla lanes? Spatial use and equity patterns on the I-394 MnPASS lanes. URL: https://conservancy.umn.edu/handle/11299/179829 (Last accessed: Aug, 2022)

Sanchez, T. W. (2008). Poverty, policy, and public transportation. *Transportation Research Part A: Policy and Practice*, *42*(5), 833-841.

Sigo, S. (2018). Anti-toll movement may upend North Carolina's first transportation P3. https://www.bondbuyer.com/news/public-backlash-may-upend-north-carolinas-first-road-p3. Last accessed: Aug, 2022

Tan, Z., & Gao, H. O. (2018). Hybrid model predictive control based dynamic pricing of managed lanes with multiple accesses. *Transportation Research Part B: Methodological*, *112*, 113-131.

Transurban (2022). 495, 95, 395 Express Lanes. URL: https://www.expresslanes.com/ Last accessed: Aug, 2022.

Twaddell, H., & Zgoda, B. (2020). *Equity Analysis in Regional Transportation Planning Processes, Volume 1: Guide* (No. Project H-54).

Ungemah, D. (2016). Are Managed Lanes Equitable. *BATIC Institute Webinar Series: Priced Managed Lanes*. URL: http://www.financingtransportation.org/capacity_building/event_details/batic_webinar_managed_lanes.aspx (Last accessed Aug, 2022)

Wang, X., Yang, H., Zhu, D., & Li, C. (2012). Tradable travel credits for congestion management with heterogeneous users. *Transportation Research Part E: Logistics and Transportation Review*, *48*(2), 426-437.

WSP USA (2021). Low-Income Toll Program Study for I-405 and SR-167 Express Toll Lanes. *Recommendation report by Washington State Transportation Commission.* URL: https://wstc.wa.gov/wp-content/uploads/2021/08/2021-WSTC-Tolling-Equity-Report.pdf. Last Accessed: September, 2022

Wood, N., McGee, J., Geiselbrecht, T., & Simek, C. (2020). *Emerging Challenges to Priced Managed Lanes*. Austin, TX: National Cooperative Highway Research Program.

Zhang, Y., Atasoy, B., & Ben-Akiva, M. (2018). *Calibration and optimization for adaptive toll pricing* (No. 18-05863).

APPENDIX

Publications, presentations, posters resulting from this project:

Pandey, V. and B. G. Alamri, (2021). Dynamic Pricing on Express Lanes: A Simulation-Based Evaluation of Unintended Consequences. In *ASCE International Conference on Transportation & Development (ICTD 2021)*, ASCE, Austin TX, 2021.

Pandey, V., B. G. Alamri, and Kishumbua, K. (2021). Equitable Dynamic Pricing for Express Lanes. Presented at the *2021 Conference on Advancing Transportation Equity* (Oct 2021), and at the 2022 CATM Symposium (Feb 2022).

PDFs for the poster and presentation are attached separately to the report.