Project ID: NTC2015-MU-R-09

OPEN TOLL LANES IN A CONNECTED VEHICLE ENVIRONMENT

DEVELOPMENT OF NEW PRICING STRATEGIES FOR A HIGHLY DYNAMIC AND DISTRIBUTED SYSTEM – PHASE II

Final Report

by

Mecit Cetin, Ph.D. (PI)
mcetin@odu.edu; (757) 683-6700; (757) 686-6214 (fax)
Civil and Environmental Engineering Department
Old Dominion University

Gulsevi Basar, PhD Candidate, Old Dominion University
Andrew J. Collins, Ph.D., Old Dominion University
Erika Frydenlund, Ph.D., Old Dominion University
R. Michael Robinson, Ph.D., Old Dominion University

for

National Transportation Center at Maryland (NTC@Maryland)
1124 Glenn Martin Hall
University of Maryland
College Park, MD 20742

November, 2017

ACKNOWLEDGEMENTS

This project was funded by the National Transportation Center @ Maryland (NTC@Maryland), one of the five National Centers that were selected in this nationwide competition, by the Office of the Assistant Secretary for Research and Technology (OST-R), U.S. Department of Transportation (US DOT).

DISCLAIMER

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

EXECUTIVE SUMMARY

This project is focused on investigating and developing alternative tolling options in a connected vehicle environment. Future vehicles are expected to have full connectivity and environmental awareness with access to critical system-state information in real-time.

This project is closely related to the congestion mitigation focus area of the National Transportation Center @ Maryland (NTC@Maryland) since the proposed research supports the development of effective tolling strategies for congested freeways. In addition, the proposed research will support the Connected Vehicle Initiative of the USDOT since the tolling system to be developed is for a system where vehicles can communicate with the infrastructure.

In the first part of the project, to investigate future the possibilities for open toll lanes in a connected vehicle environment, the research project was split into two research approaches: analytical and simulation. The analytical research used a simple two route tolling scenario to analyze the effect of travelers' VOT distribution on the network. In addition to the analytical formulations of the problem, a microsimulation testbed was developed to enable assessment of alternative bidding mechanisms for the toll lanes. The simulation was built using VISSIM-VBA interface. The model involved a simple network with two parallel routes to evaluate the distribution of traffic between a toll road and a general-purpose road, and an alternative pricing mechanism based on descending price auction (i.e. descending price auction) was developed where transactions between drivers and the toll operator are assumed to take place via the V2I technology.

In this phase of the project, behavioral surveys were developed and conducted to gain insights into how people would choose to travel on toll roads when given the opportunity to bid, and whether they have support for new futuristic tolling methods enabled by V2I technology. The collected data was further incorporated into a mathematical model. The behavioral surveys were conducted in two parts: online stated preference survey and in-class game.

Data from 159 participants residing in mainly Hampton Roads region in Virginia were collected by an online stated preference survey. Analysis showed that there is no outright rejection of the descending price auction tolling among those who are familiar with the current tolling practices. While male participants are strongly supportive of the new method, there was no clear and statistically significant pattern across other demographics. Furthermore, the data were incorporated into a statistical simulation to compare revenue generation and capacity utilization by the proposed method against the fixed tolling method. It is found out that the proposed method generates significantly more revenue than the fixed tolling mechanism does.

From the in-class game data, the study involved participants viewing videos of several tolling scenarios and placing their bids for using the toll road. Three different travel time savings levels were considered for both auction mechanisms: a sealed-bid auction and a Vickrey auction. The results indicated that there was a difference in respondents' behavior between the bidding strategies for the two mechanisms, with participants bidding lower in the sealed-bid auction. According to auction theory, this result was expected.

1.0 INTRODUCTION

This report summarizes the research conducted by Old Dominion University for the National Transportation Center @ Maryland (NTC@Maryland). The main focus of this research project is to explore alternative methods for toll roads or lanes. While there have been significant developments in congestion pricing, HOT/HOV lanes, and dynamic pricing, there is limited work on investigating how different auction mechanism could be adapted to toll road operations. Even though, currently there is no tolling system in the world where an auction-based mechanism is employed to set the prices, it is reasonable to expect to see such systems in the future given the emergence of automated and connected vehicles.

1.1 BACKGROUND

The future driving experience is expected to be vastly different from today's environment: driverless vehicles will free up passengers and "drivers," allowing communication with fellow road users and infrastructure via vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications. This future transportation environment provides new opportunities for conducting road operations including new methods of tolling. Tolled travel lanes with congestion pricing are an effective method to address the growing congestion problems on freeways. In the current state of practice, toll lanes are typically separated by physical barriers from the regular lanes with toll rates either fixed or varying by time-of-day or by congestion level. Vehicles that sense their own locations (including the lane occupied) can exchange information about their positions and speeds. These attributes will serve as the basis to develop and support an open tolling system with the number of "tolled lanes" varying dynamically to maximize throughput. In addition, toll rates paid by vehicles may change not only by congestion level but by when/how the driver decides to use (or reserve) the toll lane(s). The tolls paid by users may also vary by demographic factors (e.g., income) and trip purpose if the system is designed to allow drivers to bid for the privilege of using the toll road.

1.2 RESEARCH OVERVIEW

1.2.1 Problem Statement

In previous research, this project team developed analytical solutions for a new tolling approach based on a combinatorial Vickrey auction (Vickrey, 1961) designed for a single toll road with multiple entry points where travelers can make multiple bids to gain access to part or the entire toll lane (Collins et al., 2015b). The impacts of varying the distribution of travelers' Value of Time (VOT) on the revenue earned by the toll operator has been analyzed with simplifying assumptions made about the behavior of users (Collins et al., 2015b).

In this phase II study, the team developed and conducted surveys to gain insights into whether public supports implementation of new mechanisms and how people would choose to travel on toll roads when they are given the opportunity to bid. Surveys provide a means to collect some information on individuals' bidding behaviors, even if only as stated preferences, and can be used to inform the foundation of the human behavior model of our previous research. Modeling human behavior is challenging, especially when accounting for heterogeneous behavior of drivers. The goals of phase II of this research were identified as:

- Design of stated preference survey and in-class interactive game-based survey
- Collection of survey data of stated preference of individual behavior within a future tolling scenario that requires V2I communication
- Analysis and incorporation of the survey data results into existing auction models

1.2.2 Research Objectives

The main goals of this project can be summarized under the following three categories or tasks:

Task 1: Design and Collection of Survey Data: Two survey instruments, a traditional survey and a video-based game, were constructed to inform the parameter selection for existing models and to answer behavioral questions. In both instruments, the survey questions are based on hypothetical scenarios which require the respondents to state their preferences and bid prices. These scenarios include hypothetical parallel toll and non-toll roads with their associated travel conditions. Survey participants are informed about the toll/bid mechanisms and their options for bidding. The details of the survey designs were determined after reviewing the literature on similar survey instruments for eliciting behavior where users enter bids. The traditional survey was conducted online through an established survey application disseminated via list-serves, email solicitation, and personal invitation; the video-based game survey was conducted in-person among students at Old Dominion University.

Task 2. Analysis of survey data: Based on the insights gained from the survey, a statistical analysis was conducted on the survey data to determine how people respond to and bid under different conditions. Findings from these analyses were presented as three posters at the 95th and 96th Annual Meetings of Transportation Research Board, and a poster in Automated Vehicles Symposium 2017; and extended analyses focusing on descending price tolling were published in Transportation Research Part C: Emerging Technologies in 2017.

Task 3. Incorporation of survey findings in existing tolling model: The existing analytical toll model was adapted to incorporate findings from the survey data, especially the value of time distribution and individuals' ability to anticipate other drivers' behavior as well as the toll road operator's behavior.

1.2.3 Relevance to the Center

This project is closely related to the congestion mitigation focus area of the NTC theme since the proposed research supports the development of effective tolling strategies for congested freeways. In addition, the proposed research will support the Connected Vehicles Initiative of the USDOT since the tolling system to be developed is for a system where vehicles can communicate with the infrastructure.

1.3 OUTCOMES AND DELIVERABLES

1.3.1 Papers and Posters Accepted

- Collins, Andrew J., et al. "Comparing Value-of-Time Distributions in a Tolling Auction Mechanism Enabled by Vehicle-to-Infrastructure Technology." Transportation Research Board 95th Annual Meeting. Washington, DC. No. 16-5030. 2016.
- Collins, Andrew J., R. Michael Robinson, and M. Cetin. "Survey Results Comparing Value of Time Distributions for Future Auction Tolling." Transportation Research Board 96th Annual Meeting. Washington, DC. No. 17-00977. 2017.
- Basar, Gulsevi, Erika Frydenlund, and Mecit Cetin. "Public Opinion and Attitudes Toward Auction-Based Tolling Systems in a Connected and Automated Vehicle Environment." Transportation Research Board 96th Annual Meeting. Washington, DC. No. 17-03488. 2017.
- Basar, Gulsevi, and Mecit Cetin. "Auction-based tolling systems in a connected and automated vehicles environment: Public opinion and implications for toll revenue and capacity utilization." Transportation Research Part C: Emerging Technologies 81 (2017).
- Cetin, Mecit, and Basar, Gulsevi. "Auction-based Road Pricing under Connected and Automated Vehicles." Automated Vehicles Symposium. San Francisco, CA. 2017.

1.3.2 Presentations

- Cetin, Mecit. "Tolling and auctioning in a connected vehicles environment." Presented at UMD Transportation Innovation & Policy Summit. Baltimore, MD. April 14, 2016.

1.3.3 Models & Data

- Survey Dataset 1: collected from online survey of stated preferences regarding two methods for congestion pricing via auction mechanisms (N = 159)
- Survey Dataset 2: collected from video-based game interaction with students soliciting stated preferences for bid pricing to evaluate Value of Time (VOT) for two tolling auction mechanisms (N = 151)
- Route choice modeling (binary and mixed logit models): built on the sample of 159 participants from Hampton Roads region in Virginia to analyze only one of the tolling mechanisms.
- Statistical simulation built in R analyzing and comparing fixed price tolling and descending price auction tolling based on the route choice models built above.
- Agent-based model built in VISSIM representing and comparing fixed price tolling and descending price auction tolling.
- Analytical toll model reflecting Survey Dataset 2.

1.3.4 Student Involvement/Activities

One doctoral student was fully supported by this grant while another student partially supported.

2.0 ONLINE SURVEY: PUBLIC OPINION AND ATTITUDES, AND TRAVEL BEHAVIOR

To accomplish Tasks 1 and 2 of the project, the ODU research team designed a survey distributed through an online survey platform (www.surveygizmo.com) to assess public opinions and attitudes towards the auction-based tolling mechanisms, and travel behavior and statistical implications on revenue and capacity utilization under descending price auction tolling mechanism described in Phase I of the project. This chapter describes the background, survey methodology, findings from the collected data, and choice model estimation efforts. An early version of this section including findings on second-price auction tolling was submitted as a paper to the Transportation Research Board 2017 Annual Conference, and presented in a poster session. In the extended version published on Transportation Research Part C: Emerging Technologies August 2017 issue, the focus solely remained on descending price auction tolling due to lack of accurate representation of the auction format in a static environment such as in online survey.

Traffic congestion has been a serious problem around the globe, particularly in large metropolitan areas. It imposes a huge burden on society, with negative impacts on daily life, health, the economy, and the environment. Since congestion stems from the imbalance between supply and travel demand, transportation professionals relied on the expansion of road networks to increase supply for congestion mitigation in the past. However, this approach has been proven to be impractical due to the shortage of land availability and scarce economic resources. Since roadway supply increases at much slower rate than travel demand does, policy-makers have focused on the management of demand side, particularly on congestion pricing, or tolling, which was first introduced by Pigou (1920) and later supported by Vickrey (1969).

As proposed in Vickrey's study (1969), road pricing is necessary to efficiently utilize the existing facilities in the short run while providing means to invest in future transportation systems. Thus, the toll rates should be set to match the severity of congestion. In the early stages of tolling, researchers focused on static networks with fixed toll rates. This trend, recently, switched to dynamic tolling on high-occupancy toll (HOT) lanes, and many researchers proposed different algorithms to centrally optimize traffic network from the operator's perspective in which toll rate can change by travel distance, travel demand or a feedback control mechanism (Yang, 2008; Zhang et al., 2008; Jou et al., 2012). Even though these algorithms are complicated to implement, computationally intensive, and often have operational delays in response to the real-time traffic conditions, there are several successful implementations. Examples include San Diego I-15 FasTrak toll lanes, and Minnesota I-394 toll lanes (Brownstone et al., 2003; Zmud et al., 2007).

New vehicle technologies such as connected and automated vehicles (CAVs) will be entering the roadways sooner than expected as vehicle technologies rapidly evolve. These vehicles with full automation are expected to perform all critical driving activities and make safety-critical decisions while monitoring the traffic conditions (Gasser and Westhoff, 2012; National Highway Traffic Safety Administration, 2013). CAVs will eventually free up the riders from driving tasks allowing them to engage in other activities which may as well include participating in auctions for the toll roads. Also, new types of road infrastructures such as electronic toll collection (ETC) systems increase the traffic efficiency by eliminating stop-and-go at toll booths. The deployment of these telematics technologies and enabling vehicle-to-infrastructure (V2I) communications opened new research avenues to devise dynamic toll rates based not only on network attributes as travel distance and demand, but also on the drivers' interests and willingness to pay. By giving drivers a degree of autonomy over tolls to be paid, a market competition will be created. It is practically proven that market competition adapts rapidly to the unexpected changes in economy more efficiently than centrally controlled markets. Likewise, providing a mechanism where travelers could compete for the limited roadway capacity can result in a more equitable and efficient operation. One technique to create a competitive market for toll roads is auctioning, which is proposed by Iwanowski et al. (2003) as a solution to individual route selection problem under congestion. Different auctioning techniques to ease traffic congestion are later discussed and supported by several other researchers (Markose et al., 2007; Teodorović et al., 2008; Vasirani and Ossowski, 2011; Carlino et al., 2013; Zhou and Saigal, 2014; Collins et al., 2015c; Isukapati and List, 2015; Olarte and Haghani, 2017).

Even if auction-based tolling could technically be implemented on highways today, some fundamental questions pertaining to public response and driver behavior need to be addressed. These include understanding willingness-to-pay for toll roads in an auction setting, impacts on different sociodemographic groups, and impacts on revenue and system utilization, etc. Several past studies suggest that the public is generally opposed to tolling and that public acceptance is necessary for the implementation of toll roads (Sumalee, 2001; Schade and Schlag, 2003). To alleviate public opposition to congestion pricing, some researchers suggested alternative options, such as transit incentives and subsidies on alternative un-tolled roads (Adler and Cetin, 2001). Most studies focus on similar variables, which include public awareness of the purpose of tolling, political ideology, past experiences with toll lanes, and transportation taxation, while some focused on transportation equity concerns (Odeck and Bråthen, 1997; Podgorski and Kockelman, 2006; Odeck and Kjerkreit, 2010). Second body of research studies focus on public perception of connected and autonomous vehicles. Several researchers conducted different surveys on perception about autonomous vehicles and connected vehicles, and found out that majority of the population have positive opinion on these technologies, and they express desire to have them (2014a, b). Even though researchers have focused on public attitudes towards tolling and CAV technologies separately, they have not paid attention to alternative tolling schemes under new technologies and their potential behavioral and attitudinal impacts on the public. Therefore, it is necessary to address this open question for the successful implementation of futuristic tolling techniques proposed by several studies as mentioned earlier.

In this chapter, the designed online stated preference survey to examine the public perception and attitudes towards futuristic auction tolling mechanism under fully automated and connected vehicle environments, to study their possible effects on travel and toll selection behavior, and to understand its advantages and drawbacks compared to current tolling methods (i.e., fixed tolling) is detailed.

Full automation is vital in this study since it allows passengers on board to actively engage in different activities without sacrificing safety as mentioned earlier, and this includes participating in a bidding process in an auction setting. This study particularly focuses on descending price auctions for multiple reasons. First, descending price auctions are suitable for identical and perishable goods that must be sold quickly such as fish, and tulips (Li and Kuo, 2013). The capacity slots on the highways can be treated as perishable and identical, except they can be considered multiple item auctions in which items are heterogeneous in terms of their expiration time (time when they are perished). Particularly under unexpected congestion on highways, which may occur for various reasons such as road work and incidents, this type of auction may be used to alleviate congestion in a quick manner, thanks to its speed. An earlier study showed that descending price auctions for multi-item auctions continue until all items are sold and a price vector close to competitive prices can be achieved (Mishra and Garg, 2006; Mishra and Parkes, 2009). The main contributions of this study are fourfold: i) deploying an online stated preference survey to understand public perception towards auction-based tolling mechanism enabled by V2I communication under fully automated environment, ii) showing that instead of an outright rejection, there is a support for new designs for tolling, iii) analyzing toll selection and travel behavior of respondents under descending price auctions via discrete choice models, and iv) exploring the effects of descending price auction mechanism on toll revenue and capacity utilization compared to fixed tolling.

The remainder of the chapter is organized as follows: the next section gives a brief discussion on CAVs and public attitudes towards tolling, previous auction-based traffic management studies, and different types of auctions. It is followed by the details of the proposed system built based on descending price auctions. The description of the online stated preference survey, and the methodology used to estimate discrete choice models are presented. In results section, public acceptance of such systems, estimated models, and the effects and advantages of such systems over fixed tolling are examined. The paper concludes with a discussion on the problem and study limitations to point out future research directions.

2.1 BACKGROUND

CAVs are one of the most exciting technological advances soon to be adopted in our daily transport. Companies like Google, Tesla, Audi, and General Motors have started testing their autonomous vehicle prototypes, while transportation agencies in several states such as California, Nevada, and Michigan have enacted legislation for CAVs to be tested on the roads (Schoettle and Sivak, 2014a). Several researchers analyzed and forecasted the adoption rates of these technologies under different scenarios, and according to the forecasts, it is expected that by 2045, connectivity and Level 4 automation adoption will be significant (Bansal and Kockelman, 2016). While a fast adoption is expected, public support, awareness of opinion, and concerns become increasingly important for successful CAV implementation. Different surveys in USA, UK and Australia were conducted to understand public perception on autonomous vehicles (AVs) and connected vehicles (CVs). It was found out that two-thirds of the population had heard of AVs and expressed desire to have this technology while they had initial positive opinions even though they had not heard of CV technology (Schoettle and Sivak, 2014a, b). With the coming adoption of AV and CV technologies, opportunities for alternative tolling schemes arise. However, as presented in the following sections, public acceptance and comprehension of tolling mechanisms inform actual implementation of innovative tolling strategies.

To support and manage the growing transportation demand through tolling, its public and political acceptance is essential. Schade and Schlag (2003) found very low support for different tolling mechanisms while Sumalee (2001) emphasized public acceptance as a key measurement for officials to impose tolls. Ungemah and Collier (2007) showed that the public is opposed to tolling if tolling mechanisms are complicated and unknown to drivers. While some studies find public opposition as a barrier to tolling, several studies found strong public support. Zmud et al. (2007) conducted a survey study before and after the implementation of Minnesota I-394 Express lanes and analyzed behavioral and attitudinal changes in solo drivers. They found that public support was strong among all income groups before the project's implementation and remained unchanged afterwards. As in Zmud's study, household income was frequently found to be one of the strongest determinants of public support for toll use in other studies as well (Kazimi, 1999; Li, 2001; Ozbay et al., 2006). These raised concerns about socio-economic equity of tolling roads. While Safirova et al. (2003) claims that HOT lanes greatly benefits those with more disposable income, Mowday (2006) advocates that HOT lanes are equitable for congestion relief since those who benefit the most will pay the most for the costs .

As mentioned earlier, in CAV environments, tolling agencies will have the opportunity to explore alternative tolling mechanisms that would allow price discrimination which may provide more equity as well as a potential for higher revenue generation which perhaps can be allocated for investments in transit and other modes of transportation. One of these alternative tolling mechanisms would be auctioning where drivers can bid for spots on a tolled facility that provides less congestion and more reliable travel times. Auctions facilitate competitive bidding processes in several different markets such as the foreign exchange market, flower or fish markets, and even online enterprises such as eBay. There are four basic types of auctions: ascending price, descending price, first-price sealed bid, and second-price sealed bid auctions. For more information in auction types, one may refer to Klemperer's extensive guide on auctions (1999).

Auctions enabled by V2I technologies have already been proposed by several scholars to manage traffic flow not only on road networks such as on HOT lanes, and cordon areas, but also on intersections. Teodorovic et al. (2008) introduced a system which assigns slots in an urban downtown area for vehicles to enter and visit via combinatorial auctions. Time slots to be auctioned were assumed to be three to five minutes during a day or several days. Vehicles were expected to be on time, and the auction was assumed to take place before the visit. Markose et al. (2007) implemented a sealed-bid uniform price Dutch auction in a cordon area of road network, where electronic bid submissions are received from road-users for one of limited number of capacity slots to determine second-best road-pricing across different socio-economic users. They aimed to identify which group is priced out so that alternative transport methods and policies can better target these groups to increase social welfare. The auction was used mainly to determine the market-clearing cap price. Zhou and Saigal (2014) used a combinatorial auctioning approach as well, particularly the computationally intensive Vickrey-Clarke-Groves (VCG) mechanism, to allocate traffic on HOT lanes in an interconnected traffic network in real time, where the optimal price maximizing revenue is determined first. They proved that the proposed system maximizes social utility and guarantees truthful bidding. However, the optimization problems were NP-hard when the network gets large; and authors did not specify an auction design to be implemented. Collins et al. (2015c) implemented a Vickrey auction to optimize the toll operator's revenue with HOT lane usage. They found that auction mechanism is robust to the variation of travelers' Value of Time (VOT) distribution; however, they also did not specify an auction design to be implemented in real time. Olarte and Haghani (2017) introduced a buyout lottery based traffic metering method to be used on HOT lanes or other special lanes by only utilizing from existing traffic tolling technologies, and showed its straightforward implementation as buyout auction. They developed a game theoretic model to assess the best strategy, and they showed that their proposed system alleviates congestion significantly while increasing revenue under the assumption of drivers choosing the safest strategy. Carlino et al. (2013) proposed the implementation of second price sealed bid auctions to explore whether it is possible to run auctions at multiple intersections to ease traffic flow. Vasirani and Ossowski (2011, 2012) utilized combinatorial auctions to allocate green time where drivers purchase reservation slots on an intersection network. They found out that auctioning initially decreases delays at intersections which further level off. Schepperle and Boehm (2008) proposed two different auctioning mechanisms based on drivers' valuation awareness to allow concurrent use of the intersection. These mechanisms were called "clocked", which reduced wait time for high volume traffic, and "free choice", reduced weighted wait time up to 38%. Isukapati and List (2015) proposed a multi-tiered market, where drivers pay movement managers for the priority and movement managers submit bids to infrastructure agent. Raphael et al. (2015) improved previous studies by removing vehicle agents and employing a first price single item auction based intersection control management. They showed that delay is reduced with minimal communication between agents with only utilizing the existing traffic technology, and that the system is highly reactive to changing traffic conditions.

As mentioned, different types of auctions, specifically second-price sealed bid auctions and its combinatorial derivative, were used in transportation applications. Even though the dominant strategy of truthful bidding is guaranteed, second price sealed-bid auctions are found to be more appropriate in static environments; while ascending price auctions are suitable for unique items and therefore, both were not considered in this study (Klemperer, 1999; Zhou and Saigal, 2014; Collins et al., 2015c). Descending price auctions, on the other hand, are famous for their speed, and dynamicity for perishable goods which need to be sold quickly. Particularly, under unexpected congestion, when there is no immediately available alternative route on a highway, this type of auction may work very well to alleviate congestion quickly while generating revenue for alternative transportation projects. Moreover, under multi-unit environments as it is the case in toll road capacity, descending price auctions may continue until all items are universally allocated as Ausubel (2004) offered a similar setting for ascending price auction environments (Mishra and Parkes, 2009). Mishra and Garg (2006) studied multi-item descending price auctions in an earlier work, where there are a number of sellers and buyers whose demand is at most one item. They found a dominant strategy for sellers close to a Nash equilibrium, while buyers are found to be better off waiting for price offers to drop until they may face with the risk of not winning an item. If buyers wait within this limit, it was shown that the prices close to competitive price vector can be achieved (Mishra and Garg, 2006).

2.2 PROPOSED AUCTION TOLLING MECHANISM

In this section, we present the details of the futuristic tolling mechanism that we envisioned to be enabled by V2I, and presented to the participants in the online survey.

In this mechanism, the toll operator sets an arbitrarily high toll rate and a reserve (minimum) toll rate depending on the road conditions to maintain a desired level-of-service on the toll road. The toll operator announces the toll rates to each driver individually through V2I starting from the highest toll when driver enter the toll zone, and gradually reduces the rate by a preset decrement. For example, the toll operator may start with \$10 as the first toll rate (or offer), s/he then gradually reduces the toll to \$8, \$6, and \$4 (reserve rate). In this example, the decrement is \$2 and there are four bid levels which means the driver is presented with a choice at most four times. A driver may accept any toll rate, and stop the auction at any time. For instance, if a driver rejects \$10, s/he is then presented with \$8. If the driver accepts \$8 and is accepted by the toll operator, s/he is not presented with subsequent toll rates. Each driver's demand is assumed to be a single capacity slot on toll road while the toll operator has multiple capacity slots to sell within a certain time limit, before the capacity slots expire.

As in descending price auction, in this mechanism, the auction rounds are timed. Every driver is permitted a certain time to make and communicate their decision on whether to take the toll rate and go on the toll lane. The auction ends in two conditions. First, the driver accepts a toll rate and gets accepted to toll road if there is enough capacity at the projected arrival time on the toll road. Toll road capacity is considered to be sliced by time intervals as proposed in previous studies (Ravi et al., 2007; Iftode et al., 2008). Second, the driver opts out of the auction by rejecting all price offers including the reserve (minimum) price and decides to use the toll-free lane.

In practice, multi-unit descending auctions continue as a series of single-unit auctions and they continue until the unit is sold, and for the next unit, the auctioneer starts at an arbitrarily high price (Malvey et al., 1995). This is also like the toll operator auctioning each capacity slot on the toll road separately to the drivers. Similar to Mishra's and Parkes' study (2009), at each toll rate offer iteration, the toll operator makes a decision universally across all drivers about which drivers will be tolled based on the available capacity slots to be sold and communicates the decision to the driver (bidder). The drivers who are granted the right to use toll road pay the price they accepted. With this auction setting, auctioneer, in other words toll operator, implements a price discriminating strategy. This main strategy of the toll operator is maximizing the revenue while keeping toll road's travel time reliable through maintaining its operations at the free-flow speed. Similar to Mishra and Garg's earlier study (2006), drivers have to balance the trade-off between accepting a higher toll rate and waiting for a lower toll rate offer from the toll operator but risking the chance of losing access to the toll road due to the imposed capacity restrictions to maintain free-flow speed. Though originally implemented to auction perishable items such as tulips and fish, this mechanism adapts well to tolling since spots on the tolled facility diminish as drivers bid to access the road. The access is also 'perishable' in that it is limited by the toll operator to control congestion on the tolled road.

It is anticipated that advancements in CAV technologies will significantly support different congestion solution methods by enabling drivers to access to more information on prevailing traffic conditions and cooperate through vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication (Klein and Ben-Elia, 2016). In our proposed mechanism, it is considered that connectivity and automation are both vital for several reasons. First, in this system, drivers are offered multiple tolls individually, not collectively, to assess their intrinsic valuation for the toll route, and design an individual-specific pricing. To help them decide, they are also provided with the information on travel times on different routes (i.e. toll and toll-free route) and the available capacity at the time of their projected arrival they are competing against other drivers. After deciding to accept or reject a toll offer, drivers need to be able to communicate their decision with the toll operator through V2I. Second, to digest all available information, and to assess and communicate the decision with the toll operator will impose a heavy burden on the drivers; therefore, they need to be freed up from driving tasks to not introduce any kind of danger in traffic stream stemming from distracted driving. Distracted driving can be overcome through automation. Third, the system is intended to work in real-time to manage congestion, not before trip starts as a reservation-based system. Bidding in the auction takes place during trip. Therefore, the system requires some form of robust communication between drivers and the toll operator which minimizes the message transmission delay and the loss of communication (i.e. data packet loss).

Finally, it is considered that for vehicles, which will be traveling on toll route, lane changing and overtaking should not introduce any kind of congestion near the diversion point; and it should be facilitated through communication between vehicles for this system to work well.

2.3 SURVEY DESIGN AND DEVELOPMENT

As mentioned earlier, an online survey was conducted using SurveyGizmo (https://www.surveygizmo.com/). The questionnaire shown in Appendix A was designed by the Old Dominion University Transportation Research Institute and approved by the university Institutional Review Board to ensure ethical human subjects research. The survey was disseminated through social media such as Twitter, Facebook, and LinkedIn, along with university announcement mass e-mails. Phone calls or paper surveys were found to be ineffective as the survey required an interactive component that allowed the respondent to review several driving scenarios within a certain case of descending price auction method as described in Section 2.2.

The survey has three sections. First part consists of the questions related to the auction-based tolling scenarios where the respondents revealed their stated preferences for the presented tolling rates while the second and third parts consist of the perception and comprehension questions about the tolling mechanics, and demographic questions respectively. The questions were given in the same order and not randomized.

2.3.1 Auction-based tolling scenarios

In the online survey, respondents were presented with three descending price auction cases, each including five bid levels to keep the length of survey tolerable and to increase participation. The cases were prepared based on low, medium, and high travel time savings (difference between travel times on toll road and toll-free road), and slow, medium, and fast auction count-down clock speeds to deliver decision. Travel time savings is abbreviated as TTS in subsequent sections.

All the respondents were informed that the purpose of the trip is to commute to or from work or school. Five price bid levels were used in each case. The highest bid was set at $54.00 per hour time savings (90 cents per minute) as a cap price, while the lowest bid was set at $6.00 (10 cents per minute). The highest bid is determined based on previous studies conducted in different states, and scaled based on Virginia's state-wide average annual income (Burris et al., 2012). The decrement between the toll rates was set at $12.00 per hour. Toll rates were scaled according to TTS between routes (i.e., for 30 minutes, the highest bid was set at $27.00 and lowest and decrement at $3.00 and $6.00 respectively). Respondents were first asked if they accept to pay the highest bid. If they accepted to pay, then they were directed to the next question in the survey. If respondents did not accept to pay toll, they were presented with the next lower price, until reserve toll rate was reached. Details of the scenarios presented to the participants are shown below in Table 1. The clock speed is the length of time available to the respondent to make a decision in each scenario. If a decision is not made within this time limit, it is assumed that the respondent has selected the toll-free option and is then presented with the subsequent toll rate until reaching the lowest rate (Toll Rate 5 as shown in Table 1).

Table 1: Descending price auction case scenarios presented in the survey

Case	Toll Road Travel Time (Min)	Toll-free Travel Time (Min)	TTS (Min)	Clock Speed (Seconds)	Toll Rate 1 ($)	Toll Rate 2 ($)	Toll Rate 3 ($)	Toll Rate 4 ($)	Toll Rate 5 ($)
1	15	20	5	60	4.5	3.5	2.5	1.5	0.5
2	15	30	15	45	13.5	10.5	7.5	4.5	1.5
3	15	45	30	30	27	21	15	9	3

Before the survey starts, a detailed written explanation of the mechanism (e.g., number of bid levels) is not provided so that the respondents make their decisions based on the presented scenario. This also minimizes the undesired behavior where the respondent may simply decide to wait for the lowest bid level. To clearly communicate the scenario, the respondents were presented with a visual depicting travel times on the toll route and the toll-free route, remaining capacity on toll road (which gradually decreases with decreasing toll rates), current toll rate offer of the toll operator, and count-down clock to make a toll acceptance decision. An example of this visual is shown below in Figure 1.

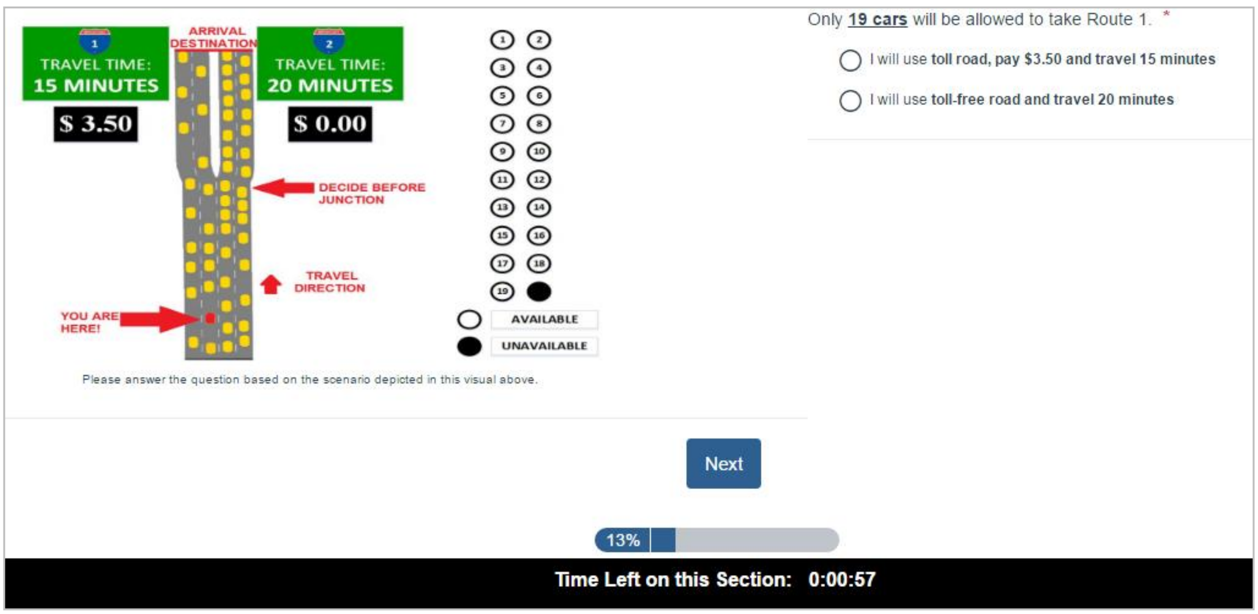


Figure 1: Sample visual depicting a proposed tolling choice question in the online survey

2.3.2 Measuring public perception and comprehension in the survey

In the opinion section, respondents were asked to rate their understanding of descending price tolling method. The scale was set from 5 ("Extremely well") to 1 ("Not at all"). Respondents whose rates were below or equal to average score 3 were asked the reasons in a comment box to indicate the shortcomings of the hypothetical system. Respondents also answered whether they were familiar with current tolling strategies in their cities. Only those who indicated positive familiarity were asked their preference among current and proposed mechanisms.

2.3.3 Demographics in the survey

In the demographics section, respondents were asked their income and age range, sex, household size, education level, employment status, and, if employed, whether they work part-time or full time. Also, they were asked whether they regularly commute and use toll roads.

2.3.4 Survey participants

The survey was conducted between March and November 2016 among the participants living in the United States. The survey was initiated 347 times, and completed 218 times. Out of 218 completed responses, only one participant did not agree to participate in the survey. A total of 194 responses were remained after discarding 23 responses due to missing or incomplete information. All participants stated that they are residing in the United States. While 159 of them stated that they reside in the state of Virginia, particularly in Hampton Roads region while the rest scattered across the US. The demographics of those residing in Virginia are shown in Table 2. As it can be seen, the demographics are biased towards highly educated, high income, and young adult respondents, which is perhaps expected since an online survey instrument is used.

2.4 DISCRETE CHOICE MODEL AND EXPLANATORY VARIABLES

To analyze the impact of various factors on choosing toll road and to facilitate revenue and capacity utilization analyses conducted in Section 2.6.3, discrete choice models are estimated based on the collected data. The route choice analysis in this study is based on two hypothetical roads, toll road and toll-free road, as shown in Figure 1. It utilizes two different techniques, binary logit and mixed logit model, to estimate the main and interaction effects of the variables. The utility function in binary logit model is defined as below:

$$\boldsymbol{U_{iq} = \beta X_{iq} + \varepsilon_{iq}} \tag{1}$$

where

$\boldsymbol{i}$ = index for route, $\boldsymbol{i = 1}$, or 2, because there are two routes in the scenarios presented

$\boldsymbol{q}$ =index of individuals

$\boldsymbol{X_{iq}}$ =vector of explanatory variables specific to individual $\boldsymbol{q}$ and route $\boldsymbol{i}$

$\boldsymbol{\beta}$ = parameters corresponding to the explanatory variables to be estimated

$\boldsymbol{U_{iq}}$ =the utility associated with route $\boldsymbol{i}$ for individual $\boldsymbol{q}$

$\boldsymbol{\varepsilon_{iq}}$ =random term identically and independently Gumbel distributed across routes and individuals

The random error term is assumed to be identically, and independently standard Gumbel distributed across alternatives. The probability of a participant choosing route i over route j is given by:

$$\boldsymbol{P\,(U_{iq} > U_{jq}) = \frac{e^{\beta X_{iq}}}{e^{\beta X_{iq}} + e^{\beta X_{jq}}}} \tag{2}$$

The mixed logit model is a highly useful and flexible random utility model, and it overcomes several limitations that standard logit model has. These limitations include random taste variation, and correlation among unobserved factors (Train, 2009). In order to account for

Table 2: Demographics of the Virginian participants

Segmentation	Subgroup	Number of participants	Size of the group (%)
Gender	Female	84	53%
	Male	75	47%
Age	16 - 24 years	17	11%
	25 - 40 years	71	45%
	41 - 65 years	60	38%
	65+ years	11	7%
Educational Attainment	High school or less	6	4%
	Associate degree	25	16%
	Undergraduate degree	57	36%
	Graduate degree	71	45%
Employment Status	Unemployed	6	4%
	Other	13	8%
	Full-time	117	74%
	Part-time	23	14%
Annual Household Income	Low (Less than $34,999)	22	14%
	Medium ($35,000 - $49,999)	17	11%
	Upper medium ($50,000-$99,999)	62	39%
	High ($100,000 or more)	58	36%
Household Size	1	20	13%
	2	71	45%
	3	29	18%
	4	21	13%
	5+	18	11%
Commute	Commuter (Driving)	147	92%
	Non-commuter	12	8%
Total participants		159	100.00%

correlation across alternatives and choice situations, the error term is divided into two components. The utility function associated with alternative i in a given choice situation t for an individual q takes the following standard form:

$$\boldsymbol{U_{iqt} = \beta X_{iqt} + [\eta_{iq} + \varepsilon_{iq}]} \quad (3)$$

Where

$\boldsymbol{i}$ = index for route, $\boldsymbol{i = 1}$, or 2, because there are two routes in the scenarios presented
$\boldsymbol{q}$ = index of individuals
$\boldsymbol{t}$ = index for choice situation individual $\boldsymbol{q}$ is facing

$\boldsymbol{X_{iq}}$ = vector of explanatory variable specific to individual $\boldsymbol{q}$ and route $\boldsymbol{i}$
$\boldsymbol{\beta}$ = parameters corresponding to the explanatory variables to be estimated
$\boldsymbol{U_{iq}}$ = the utility associated with route $\boldsymbol{i}$ for individual $\boldsymbol{q}$
$\boldsymbol{\eta_{iq}}$ =random term dependent over individuals and underlying data and parameters
$\boldsymbol{\varepsilon_{iq}}$ =random IID term with zero mean and independent of underlying parameters and data

In the mixed logit model specification, η is assumed a general distribution such as normal, lognormal, uniform and triangular distribution. The conditional choice probability of an alternative for an individual q in the choice set for a given value of η is calculated as shown below. Since the value of η is not given, the probability is calculated by integrating over all values of η.

$$\boldsymbol{P(\beta_q | \eta_{iq}) = \frac{e^{\beta_q X_{iq} + \eta_{iq}}}{\sum_j e^{\beta_q X_{jq} + \eta_{jq}}}} \tag{4}$$

In this study, mixing distributions among parameters are normal distribution. The choice probabilities are calculated based on simulation-based maximum likelihood estimation method. Halton draws for the values of η are considered since their efficiency have already been proven (Bhat, 2003; Train, 2009).

2.5 SIMULATION OF ROUTE CHOICE BEHAVIOR

To get a better understanding of the descending price auction mechanism, it would be interesting to compare the system performance under the proposed tolling mechanism to that under the traditional fixed tolling system in a statistical simulation environment.

To compare the two tolling systems, a hypothetical network like the one presented in Figure 1 with two parallel routes, a toll road and toll-free road, is considered. For both tolling options, the route choice behavior is modeled based on the mixed-logit model presented subsequently in Section 2.6.2. In other words, it is assumed that the route choice behavior under fixed tolling could also be described by the same choice model. While this seems to be a restrictive assumption, one can argue that fixed tolling is a special case of descending auction where only one price is offered. In this case, it is assumed that minimum and maximum toll rates offered by the toll authority are the same, and the price decrement is assumed to be zero.

In descending price auction, the toll operator has two aims. One of these aims is to provide a certain level of service by maintaining free-flow speed on toll road. To do that, toll operator accepts vehicles on toll road based on the available capacity. The second aim is to maximize the revenue. Toll operator achieves that by sorting accepted bids in descending order and accepts only the highest ones based on the desired capacity level. With these two aims, toll operator in descending price auction mechanism attempts to achieve full capacity utilization and revenue maximization by optimizing the initial and reserve toll rates and the decrement. On the other hand, with fixed tolling, the toll rate that maximizes revenue is not necessarily the same toll rate that maximizes the throughput on toll road. Therefore, to make a fair and meaningful comparison with fixed tolling, the specific toll rates which maximize (i) capacity utilization and (ii) revenue in fixed tolling should be analyzed separately to understand how each one of these two options performs against the descending auction price mechanism. In the simulation, descending price auction with five toll rates (bids), and same minimum and maximum toll rates (per minute of TTS) is compared to fixed tolling (see Section 2.6.3.1). The sensitivity of simulation results to toll road capacity (see Section 2.6.3.2) as well as the implications of descending price auction on different income groups are demonstrated (see Section 2.6.3.3). Moreover, descending price auction with different number of bid levels under exact similar situation is simulated to evaluate how the number of bid levels affect the collected revenue and capacity utilization (see Section 2.6.3.4).

2.6 RESULTS AND DISCUSSION

2.6.1 Acceptance of the proposed method

Eighty-eight out of 159 respondents (55%) stated familiarity with the current toll mechanism in their respective geographical areas. Fifty-eight percent of those respondents supported the descending price auction-based tolling mechanisms introduced in the survey, while the remaining preferred current tolling mechanism they are familiar with, as shown in Figure 2. Respondents rated their understanding and comprehension of how descending price auction mechanism works above average with an average score of 3.63 out of 5.00. While respondents familiar with tolling in their respective regions rated their understanding with an average of 3.74, respondents with no familiarity rated their comprehension as 3.49. The analysis of opponents' comments gave important insights into shortcomings of proposed methods. Some opponents stated that they dislike paying tolls in general, and they consider looking for toll-free routes on their journey. As studied in earlier studies, rather than the proposed method, this may stem from low level of public awareness among the actual use of general toll collections and toll projects, and this barrier may be overcome through proper education on congestion pricing (Odeck and Bråthen, 1997; Ungemah and Collier, 2007). Moreover, both opponents and supporters of the proposed method expressed that variable tolls are confusing, and difficult to master to understand how the prices are determined. They also stated confusion over limited capacity slots on toll road. This suggests that proper education and information on bidding and the proposed method, along with tolling should be given to the public when a new pricing method is introduced.

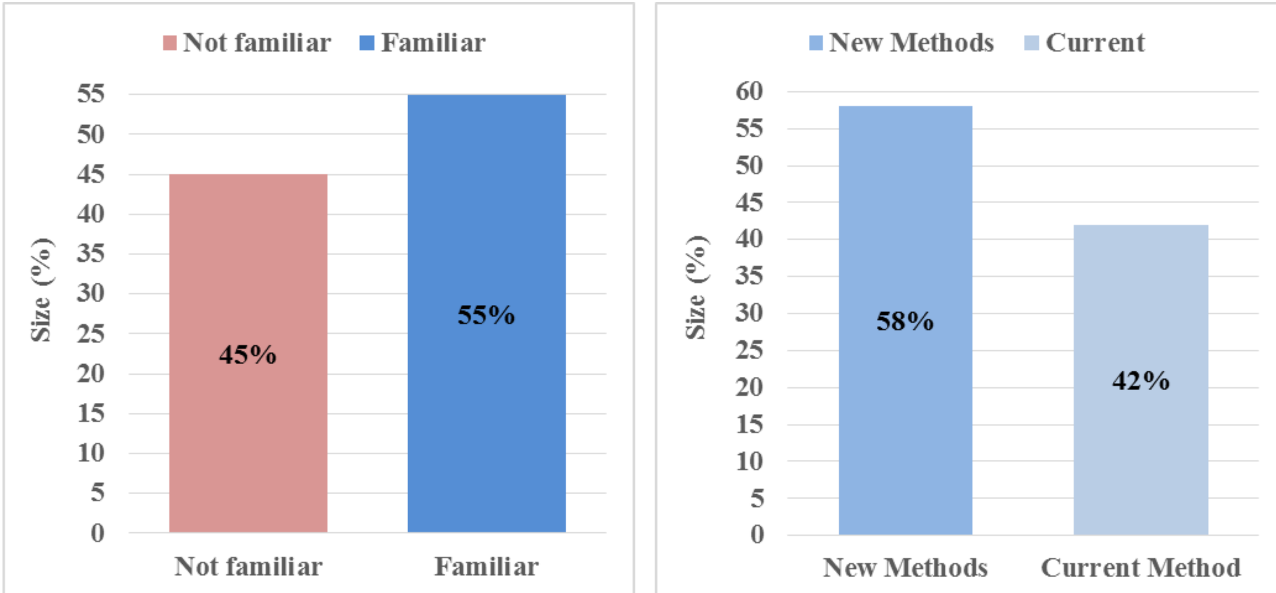


Figure 2: Indicated toll familiarity of the participants (left) and indicated preference for tolling method (right)

Toll preference and support for new method was also found to vary across demographics. Fifty-six percent of female respondents and fifty-five percent of males reported familiarity with toll roads. Among these respondents, forty-seven percent of the females supported new mechanism, while seventy-one percent of males showed support, and the support for the new mechanism by genders showed a significant difference. Moreover, the support for new method varied over age, education and income level as well. Although older respondents seemed to be more likely to support the new mechanism, there was not found a statistical difference between age categories. Like age, there was no statistical difference across different education levels and income levels. Even though there was a clear pattern across different education levels, and respondents with at least an undergraduate degree showed stronger support for introduced toll method compared to those who have less than college degree, there was no clear pattern for different income groups, and support for the new method was found to drop off at higher income levels.

2.6.2 Model estimation and behavioral meaning of parameter estimates

A binary logit model and mixed logit model with simulation-based maximum likelihood based on 100 Halton draws were separately estimated to predict the choice of accepting or rejecting a toll rate offer delivered by the toll operator. The analyses of the choices and results are presented in this section.

Before the analysis and model estimation, the data obtained were first restructured. As shown earlier in Table 1, three different scenarios are defined based on three TTS levels. Within each scenario, five different bid levels, or toll rates, were devised. At each bid level (toll rate) shown to the respondent, the respondent had two alternatives to choose from. These alternatives are "using toll-free lane" and "paying toll rate to save time". As it was shown on Table 1 earlier, we assumed that travel time on toll road is fixed to be 15 minutes, while it changes on toll-free lane in each case and assumed to be longer than travel time on toll-road by the indicated TTS. Each bid level is an independent choice situation for the respondent. At each choice situation faced, the respondent is expected to choose between two alternatives: toll route by paying toll rate corresponding to bid level and toll-free route. Therefore, in the designed survey, a respondent may have had at most five different observations per case, where TTS stays the same, but toll rates decrease dependent on a pre-defined toll decrement starting from “Toll Rate 1” (the highest) to “Toll Rate 5” (the lowest).

To better understand data restructuring process, an example of raw data and its corresponding restructured version are shown on Table 3 and Table 4, respectively. In the raw data, it can easily be seen that Person 1 was not presented with the remaining four toll rates since he accepted “Toll Rate 1” (the highest) in the first-choice situation he faced with. On the other hand, Person 2 accepted the third highest toll rate, and was not presented with the next two lower toll rates while Person 3 did not accept any toll rate shown to him, and opted to use toll-free lane. When restructuring the data, only one observation with the chosen alternative of using toll-lane by paying “Toll Rate 1” comes from Person 1 since he was only exposed to one choice situation. The data from Person 2 were structured into three observations as he faced with three choice situations until he accepted to pay toll rate and use toll-road, while Person 3 faced with five different choice situations and picked to use toll-free lane in every choice situation. For this example of three respondents, a total of nine observations were created as shown in Table 4.

Table 3: Raw survey data before restructuring

	Case 1 Toll Rate 1 Decision	Case 1 Toll Rate 2 Decision	Case 1 Toll Rate 3 Decision	Case 1 Toll Rate 4 Decision	Case 1 Toll Rate 5 Decision
Person 1	Toll-lane	N/A	N/A	N/A	N/A
Person 2	Toll-free	Toll-free	Toll-lane	N/A	N/A
Person 3	Toll-free	Toll-free	Toll-free	Toll-free	Toll-free

Table 4: Structured survey data obtained from raw data in Table 3

Respondent ID	Toll Rate	Case Number	TTS (associated with Case 1)	Choice
Person 1	Toll Rate - 1	1	5 minutes	Toll-lane
Person 2	Toll Rate - 1	1	5 minutes	Toll-free
Person 2	Toll Rate - 2	1	5 minutes	Toll-free
Person 2	Toll Rate - 3	1	5 minutes	Toll-lane
Person 3	Toll Rate - 1	1	5 minutes	Toll-free
Person 3	Toll Rate - 2	1	5 minutes	Toll-free
Person 3	Toll Rate - 3	1	5 minutes	Toll-free
Person 3	Toll Rate - 4	1	5 minutes	Toll-free
Person 3	Toll Rate - 5	1	5 minutes	Toll-free

As shown in **Error! Reference source not found.**, each choice situation the respondent faced with is treated as a separate observation in the model estimation procedure, and the interdependence between consecutive choice situations were ignored for simplicity. Overall, across 3 cases, 2072 observations are obtained and used in model estimation. The restructured data was weighted based on income levels of the Hampton Roads area population (Hampton Roads Planning District Commission, 2016). The population size, and sample size of each income level along with used weights are shown in Table 5.

Table 5: Population and sample size percentages by income groups and weights used in model estimation

	Sample	Population	Weight
Low (Less than $34,999)	14%	20.30%	1.47
Medium ($35,000 - $49,999)	11%	12.70%	1.19
Upper medium ($50,000-$99,999)	39%	36.70%	0.94
High ($100,000 or more)	36%	30.30%	0.83

Results for the final specifications of both binary logit and mixed logit model are reported in Table 6. Tested variables were in the utility function for accepting a toll rate, while the utility of choosing toll-free lane was taken as base and set to be zero. These specifications were obtained based on statistical fit and conceptual validity of model parameters.

Table 6: Model estimation results for binary and mixed logit model

	Binary Logit Model			Mixed Logit Model		
	Parameter Estimate	Standard error	t-Statistics	Parameter Estimate	Standard Error	t-Statistics
Fixed parameter						
Constant	-2.621		-10.160	-3.088	0.658	-4.696
Toll rate	-0.254		-20.480	-1.063	0.117	-9.094
Travel time savings	0.109		13.390	0.278	0.026	10.941
%-age count-down clock time for response	1.194		3.494	--	--	--
Commute	0.545		2.285	1.289	0.698	1.847
High income ($ 50,000 or more)	0.356		2.560	0.753	0.428	1.76
Standard error of parameter distribution						
Constant	--		--	1.236	0.363	3.401
Toll rate	--		--	0.517	0.063	8.23
Travel time savings	--		--	0.093	0.022	-4.282
Log-likelihood		-765.74			-641.57	
2k – 2LL		1543.48			1299.14	

In binary logit model specification, toll rate, travel time savings, percent use of count-down clock time by each respondent, commute and income parameters were found to be statistically significant at 95% confidence level. As expected, when toll rate offer is high, the utility for the toll road decreases; therefore, the coefficient is negative. When travel time savings increase, intuitively, the utility to use toll-road for the respondent increases, and the coefficient is positive. Moreover, time used to accept or reject a toll rate offer is normalized within each case based on the count-down toll clock speed (i.e. if a respondent took 15 seconds to answer a toll rate offer in Case 1 - Table 1, the time use becomes 25%), and used as a parameter to see whether it affects the respondents' decisions. The parameter was found to be statistically significant with a positive coefficient, which implies that the longer the respondent waits for accepting a toll rate, the utility of using toll road increases for that user. Similar to earlier studies mentioned, in descending price auction, the strategy for buyers (respondents or toll users in this case) is to wait until there exists a risk of not winning the offered item (Mishra and Garg, 2006). Among demographics parameters, only income level was found to be statistically significant. Other parameters such as age, gender, education level and household size did not have statistically significant effect on the utility. Although there were four income groups in the survey, it was found to be useful to combine low and medium income groups within "annual income under $50,000" and taken as base, while upper medium and high income were combined as "annual income $50,000 or more." Among different income groups, respondents with higher income levels tended to accept higher toll rates, as expected. The average money value of travel time savings per hour, in other words willingness to pay to save one-hour travel time, is calculated to be $25.75. Unlike several studies, we do not find it useful to report this willingness to pay as a percentage of hourly wage since we do not have information on the respondents' exact annual income and their share in the household. Finally, respondents who identified themselves as regular commuters were more likely to accept higher tolls.

In mixed logit model specification, distribution of parameters was fitted with normal distribution. Constant, toll rate, TTS, and percentage count-down clock time for response were variable among participants. Fixed parameter and standard error of parameter distributions were found to be statistically significant for the constant, toll rate, and TTS. At 95% confidence interval, toll rate coefficients lie between -0.029 and -2.097. For TTS, at 99.7% confidence interval, nearly all coefficient values lie between 0.000 and 0.556. These values make sense and intuitive as one expects that utility increases when TTS is higher and therefore, its coefficient should not be negative. On the other hand, increasing toll rate decreases utility, and its coefficient should not be positive for most of the population. The average money value of travel time savings was found to be $15.70 per hour, which is lower than binary logit specification. This is attributed to the nature of mixed logit model accounting for heterogeneity across individuals through the correlation between the respondents' answers across different cases. On the other hand, neither fixed parameter nor standard error of parameter distribution was found to be statistically significant for percentage count-down clock estimation; thus, the parameter was omitted from the specification. Respondents' income level and commute status remained statistically significant in this specification as well. Since the mixed logit model specification showed great improvement over its binary logit counterpart, as indicated by the log-likelihood statistics, this model specification was used for the simulation analysis explained in the next section.

2.6.3 Analyses based on the simulation data

To gain additional insights and to compare the descending price auction to the fixed price tolling, a reproducible simulation analysis was conducted in R-Studio environment (RStudio, 2014). For the simulation, at each simulation run, travel demand is assumed to be 3,000 vehicles per hour and a population of 3,000 drivers were randomly created based on the income and commuter population distribution of Hampton Roads region in the state of Virginia (Hampton Roads Planning District Commission, 2016). The desired capacity of the toll road is assumed to be 1,800 vehicles per hour in the base simulation and it was varied between 1,500 and 2,100 vehicles per hour for different simulation experiments. On the other hand, maximum and minimum toll rates are set to $0.90 and $0.10 per minute time savings, while travel time savings varied between 10 minutes and 30 minutes to test the sensitivity of results. In the simulation, fixed parameters and parameter distributions estimated in mixed logit model were used to draw coefficients for each driver. Each driver was assigned to have a uniformly drawn random probability of internal threshold for accepting a toll offer. It is assumed that drivers are asked to bid in advance of the toll lane diverge so that they have enough time to make necessary lane changes without causing congestion. The simulation was run 100 times and the average of some key outputs such as collected revenue, and toll road capacity utilization were calculated.

In the simulation, four different sensitivity analyses are conducted. First, sensitivity to travel time savings, and its implications on the collected revenue and the capacity utilization in both fixed and descending price auction tolling are analyzed. Then the effect of toll road capacity on revenue generation under different tolling systems is investigated. The implications of descending price auction tolling on different income groups are also explored to understand how the system affects high and low-income groups differently. The results are presented in Section 2.6.3.1, Section 2.6.3.2 and Section 2.6.3.3, respectively. Finally, the effect of the number of bid levels in descending price auction mechanism (the number of times the driver is asked a toll rate) is evaluated to understand how it affects the revenue collected, and the results are reported in Section 2.6.3.4.

2.6.3.1 Revenue and capacity utilization under fixed and descending price auction tolling

In this section, the collected revenue and capacity utilization under both fixed tolling and descending price auction tolling are compared. As mentioned earlier, in descending price auction tolling, the toll operator attempts at achieving both revenue and capacity utilization maximization. For comparing the two tolling options, the rate to maximize revenue and the rate to maximize capacity utilization are separately taken into consideration to make a meaningful comparison with the descending price tolling, as explained in Section 2.5.

In descending price mechanism, the sensitivity analysis of different travel time savings (TTS) levels was conducted. The number of bid levels and the decrement were set to 5 and $0.20 respectively as they were in the survey. The toll rate offer, which was accepted by each driver, was calculated based on the utility function estimated with mixed logit model in the previous section. TTS were set to be 10, 15, 20, 25, and 30 minutes. After extracting drivers who accepted a toll rate offer to be on toll road, the accepted toll rates were sorted in descending order, where ties were arbitrarily broken. Only the first 1800 vehicles were considered to pay accepted toll rate and be on toll road to maximize revenue and not to exceed desired capacity of toll road. In fixed price mechanism, for the same levels of TTS used in descending price auction, fixed toll rates which vary between $0.05 and $0.90 per minute of travel time saved are tested separately to find two specific toll rates: revenue maximizing and toll-road throughput maximizing tolls. The system performance under these two different fixed tolling scenarios is compared to the performance under the auction-based tolling.

It is found out that the fixed toll rate which maximizes revenue is not necessarily maximizing the toll-road capacity without causing congestion. Keeping the toll road uncongested is the secondary objective for the toll operator in descending price auction tolling. Therefore, the fixed toll rate which maximizes percent capacity utilization of the toll road with no congestion is taken as a comparison for the two methods as well. Toll rates maximizing revenue and percent capacity utilization in fixed tolling along with average toll rate accepted in descending price auction tolling are presented below in Table 7.

Table 7: The toll rates obtained from fixed and descending price tolling simulation

	Fixed Tolling Method		Descending Price Auction Tolling			
TTS (minutes)	Revenue Maximizing Toll	Capacity Utilization Maximizing Toll	Average Accepted Toll	Minimum Toll	Maximum Toll	Toll Decrement
10	$ 2.50	$ 1.00	$ 2.94	$ 1.00	$ 9.00	$ 2.00
15	$ 3.00	$ 1.95	$ 4.28	$ 1.50	$ 13.50	$ 3.00
20	$ 4.00	$ 3.10	$ 5.89	$ 2.00	$ 18.00	$ 4.00
25	$ 5.00	$ 4.30	$ 7.56	$ 2.50	$ 22.50	$ 5.00
30	$ 6.00	$ 5.45	$ 9.27	$ 3.00	$ 27.00	$ 6.00

On the left side of Figure 3 below, the total revenue collected by the two pricing methods across simulation scenarios is shown. The figure is created based on the revenue maximizing fixed toll prices and average accepted toll prices in descending price auction tolling shown in Table 7. As it can be seen, descending price auction tolling yields higher revenue for the toll operator across all tested TTS. This is expected since the drivers wait for the price that is equal to or below their intrinsic evaluation for the given traffic conditions; and accept the toll operator's price offer as soon as it becomes equal to or drops below their valuation. Therefore, in descending price auction, the toll operator has a chance to discover the drivers' willingness-to-pay and transfer the consumer surplus to toll operator as revenue. The transferred consumer surplus in descending price auction mechanism is what enables toll operators to extract higher toll rates per person on average compared to its counterpart revenue maximizing fixed toll rate, as shown in Table 7 above. The percent increase in revenue collected (as compared to the revenue under fixed tolls) range between 105% and 70% for 10 to 30 minutes TTS scenarios.

On the right side of Figure 3**Error! Reference source not found.**, the capacity use of the toll road by two pricing methods across simulation scenarios is shown. The figure is created based on the capacity utilization maximizing fixed price without causing congestion on toll road and average accepted toll rate in descending price auction tolling as shown in Table 7. It can be easily seen from the graph on the right in **Error! Reference source not found.** that descending price auction tolling is providing better and higher toll road capacity utilization than fixed tolling method does. The reasoning behind this is that fixed tolling does not allow drivers with lower valuation to go on toll road, and therefore, create an unutilized capacity; while descending price auction allows drivers with valuation lower than the average price paid to go on toll road to make sure the capacity is used before it perishes.

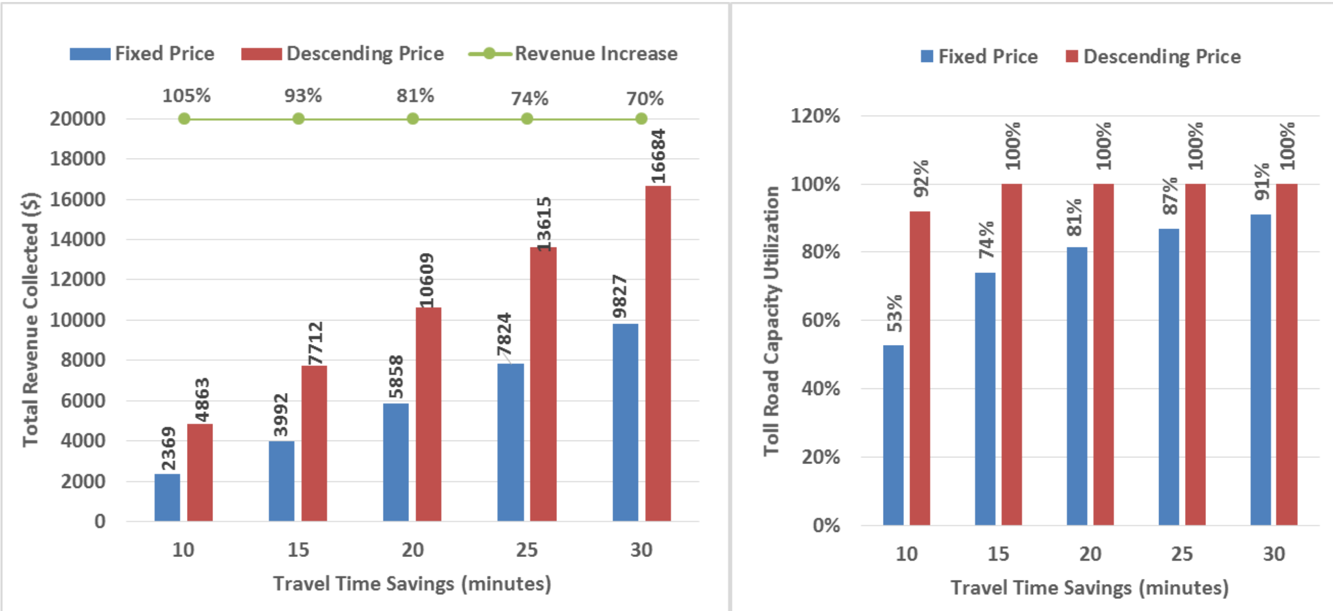


Figure 3: Comparison of revenue collected (left) under revenue maximizing fixed toll rate, and toll road capacity utilization (right) under utilization-maximizing fixed toll rate

2.6.3.2 The effect of toll road capacity on revenue generation under fixed and descending price auction

In this section, the results of sensitivity analysis of both fixed and descending price auction tolling in terms of the toll road capacity are reported. To understand how available road capacity affects the revenue collected, and capacity utilization, toll road capacity was varied between 1500 and 2100 vehicles per hour by increments of 100. Two different TTS levels are used in the simulation, 15 minutes and 30 minutes respectively, to explore whether TTS influences the sensitivity of the results to the changes in desired capacity. It is found that in fixed tolling, the maximum revenue remains the same. This is expected since the increase in available capacity does not affect the internal valuation of drivers accepting or rejecting toll. On the other hand, in descending price auction mechanism, while revenue increases, average toll price accepted by toll users decreases as the capacity increases. This is due to toll operator's aim of simultaneous maximization of capacity utilization and revenue maximization. When capacity gets larger, toll operator accepts more drivers possibly with lower valuation. Consequently, total revenue increases while average toll paid goes down. These findings are shown below in Figure 4 for 15 minutes TTS. Due to space limitations, the results when TTS is 30 minutes are not reported; however, it is important to note that the behavior of the system remains the similar.

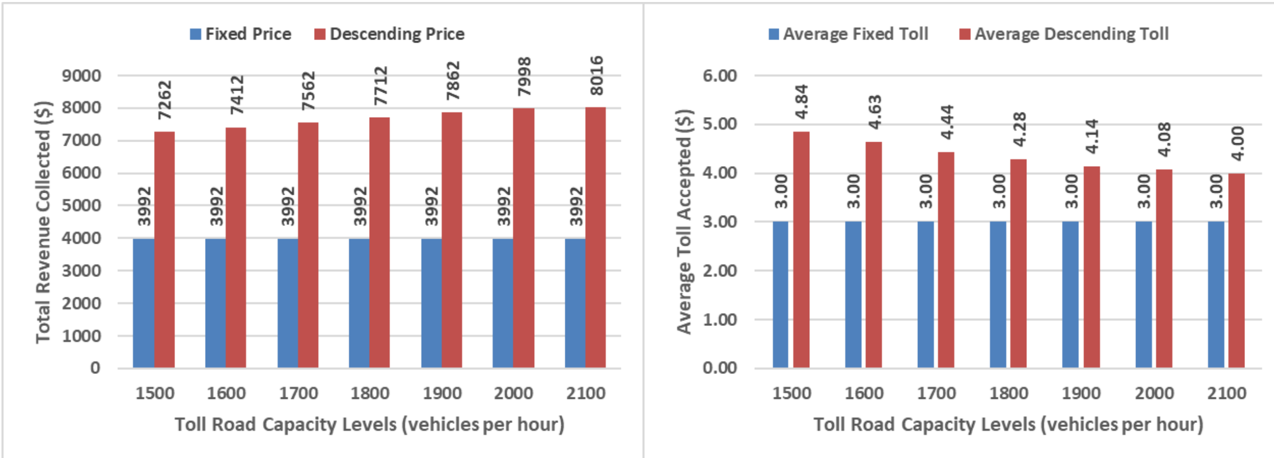


Figure 4: The effect of desired toll road capacity level on revenue collected and average toll accept by drivers (TTS: 15 minutes)

The capacity utilization in fixed tolling decreases since the available slots are increasing while the number of toll road users remain same. In descending price auction, since the aim of the toll operator is to maximize revenue and utilization simultaneously by selling all slots to the potential toll users, capacity utilization remains same at 100% level up to 2000 vehicles per hour. Beyond that, it starts decreasing for 15 minutes TTS while for 30 minutes TTS, it does not. The reason behind this is that there are not enough drivers who would like to pay at least the minimum toll (reserve toll) to be on toll road at 15 minutes TTS. To reach 100% capacity utilization, this can be resolved by changing minimum toll. The findings regarding capacity utilization under descending price auction mechanism are shown below in Figure 5.

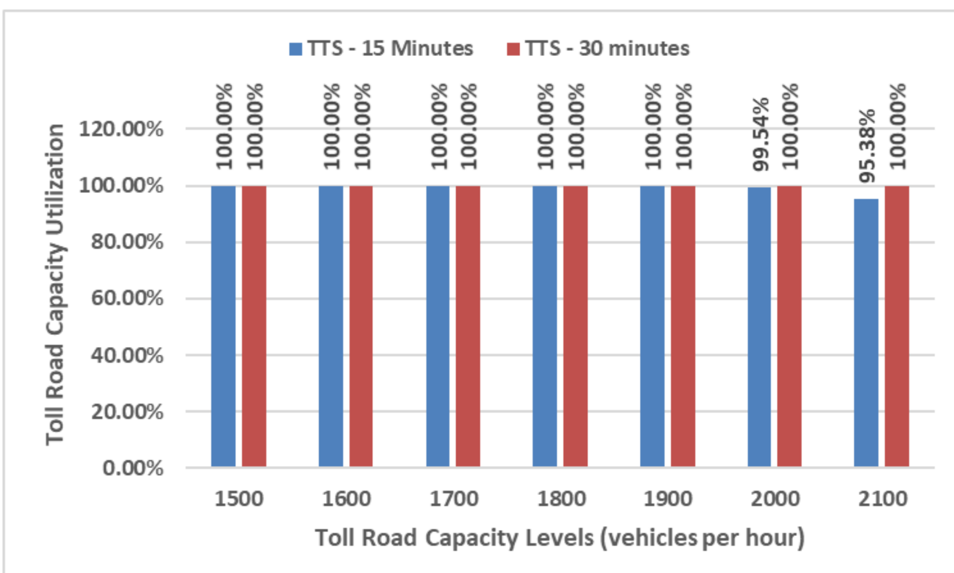


Figure 5: The effect of desired toll road capacity on toll road capacity utilization in descending price auction under different TTS (15 minutes and 30 minutes)

2.6.3.3 Implications of descending price auction tolling on toll acceptance of different income groups

Another analysis of how drivers from different income groups behave under the new tolling method was conducted. The aim for this analysis is to understand what percentage of the drivers on toll road are in high (annual household income more than 50,000K) and low income groups (annual household income less than $50,000K), and what percentage of drivers who were willing to go on toll road are rejected due to capacity restriction. In Figure 6, for each TTS, the average ratio of drivers who accept or reject to use toll road is shown across incomes. High income drivers accepted a bid more than rejecting while more low-income drivers accepted bid when TTS is higher. Among drivers in different groups who accepted a toll rate, the acceptance ratio by the toll operator is slightly higher in high income drivers, in other words, rejection ratio of low income drivers is slightly higher as shown in Figure 7. This may stem from the fact that high income drivers have higher value of travel time. Since high income drivers tend to accept higher toll rates and the toll operator's aim is to maximize revenue, toll operator ends up with accepting more drivers with the highest toll rates and high income.

The proposed system may be considered by public and researchers that it favors those who have more disposable income, and therefore, it may create transportation inequity. However, the results of simulation study suggest that this may not be an issue although it should be kept in mind that the survey data in this study were biased towards high income people, and income groups were combined due statistical convenience. With a larger sample size and with more refined income groups (more than two income groups as it is in this case), which income groups are priced out shall be discovered further in the future as this is not the scope of this study. Additionally, even though certain income groups may be priced out, it should be emphasized that the system comes with many benefits such as improved capacity utilization and increased revenue generation to invest in different transportation projects such as expansion of road networks, improvement in public transit systems and active transportation modes, along with incentives for active commute modes.

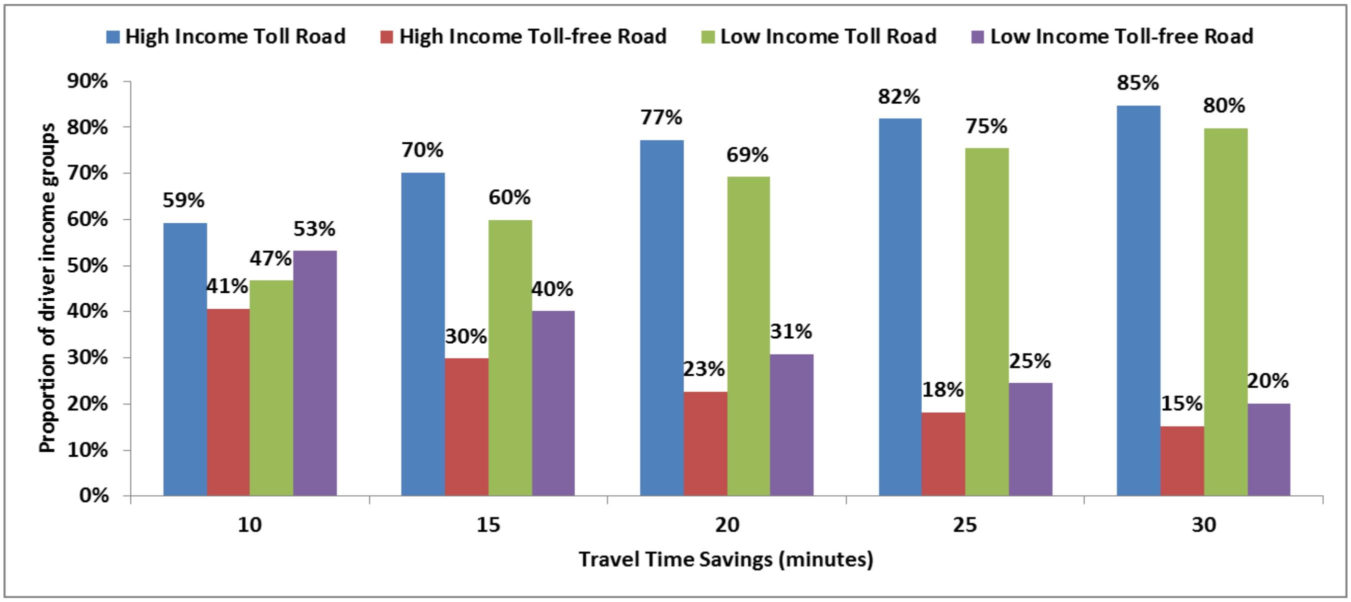


Figure 6: Ratio of drivers who accept or reject to use toll road across income groups

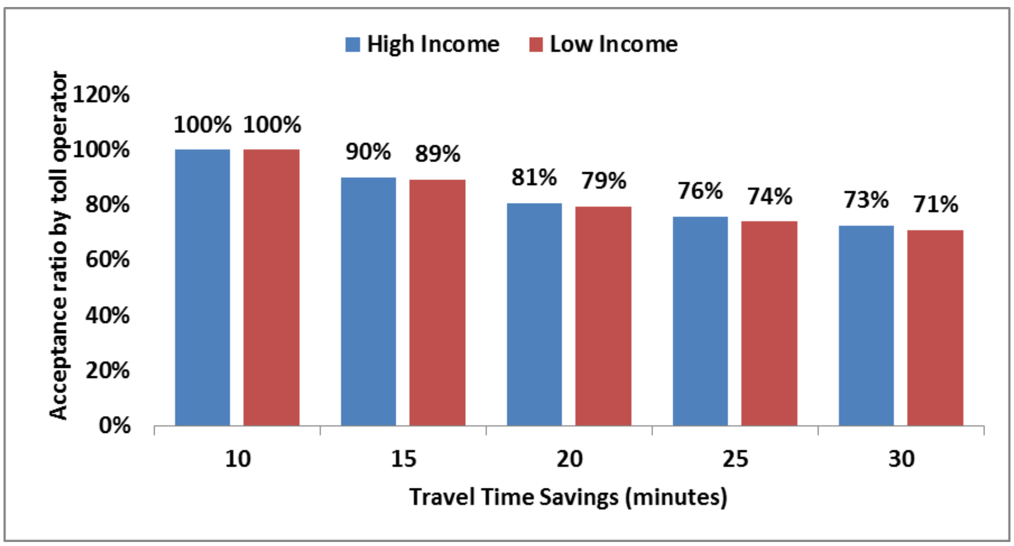


Figure 7: Toll operator's acceptance ratio of drivers across different income groups

2.6.3.4 The effect of the number of bids on revenue and capacity utilization in descending price auction tolling

The effect of the number of bid levels on the revenue and percent capacity utilization was analyzed to understand how often the toll rates should be offered without excessively interfering with the driving experience. The maximum and minimum toll rate offers were set to be \$0.10 and \$0.90 per minute TTS, which for illustration purposes was selected to be 15 minutes (other TTS scenarios will have similar patterns). The toll rate offer decrement was calculated based on the number of bid levels tested. For example, at five bid levels with minimum, \$0.10, and maximum, \$0.90, the decrement is set to be \$0.20 and the toll rate offers become \$0.90 - \$0.70 - \$0.50 - \$0.30 - \$0.10 per minute TTS; while at two bid levels, the decrement is set to be \$0.80, and the toll rate offers become $0.90 - $0.10 per minute TTS. The number of bid levels tested varied between 2 to 10 to see how many bid levels are appropriate to implement. In Figure 8**Error! Reference source not found.**, the revenue collected at each bid level along with the increase in revenue due to increasing bid level by one (i.e. from 2 bid levels to 3 bid levels, the increase in revenue collected is 27.43%) are shown. As it can be seen, after six bid levels, no significant improvement in revenue is obtained since it drops below 5%. Capacity utilization on the other hand remains the same at 100% for all bid levels, as it is not affected by the number of bid levels, but by TTS.

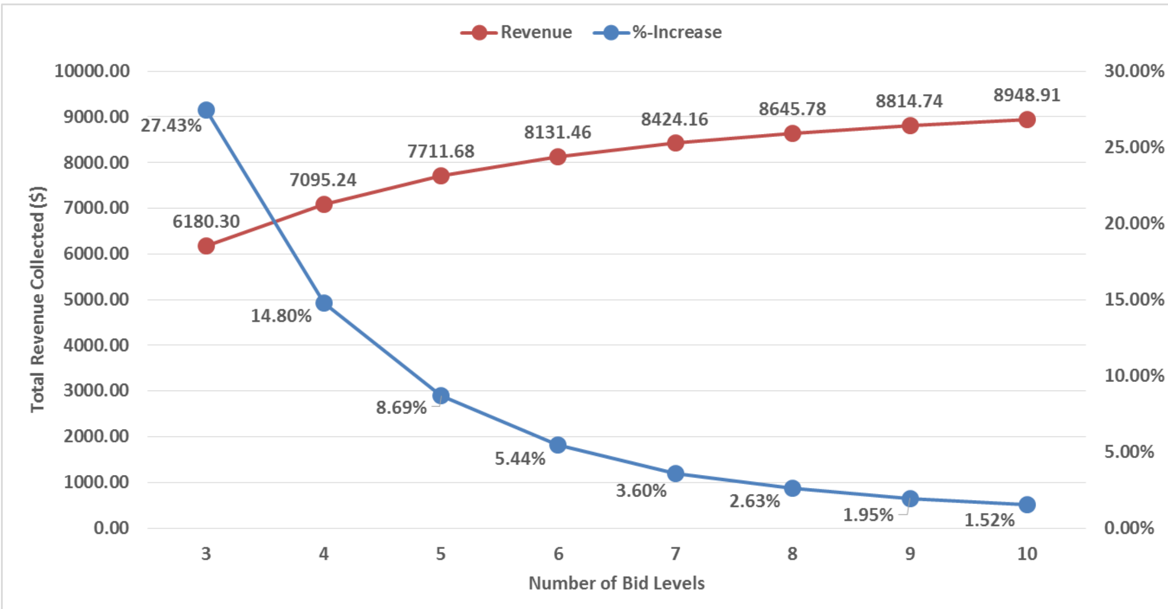


Figure 8: The effects of the number of bid levels on revenue collected at TTS 15 minutes

2.7 RECOMMENDATIONS AND USDOT RELEVANCE

2.7.1 Conclusions

In this research, public attitudes toward and comprehension of a futuristic tolling method based on descending price auction were examined. An online survey was designed and deployed among drivers, and the analysis of support for the new method across different demographics, and the estimation of toll selection choice model were conducted among 159 participants residing in mainly Hampton Roads region in Virginia. Analysis showed that there is no outright rejection of the introduced method among those who are familiar with the current tolling methods (i.e. fixed toll and dynamic tolls). Male participants are strongly supportive of the new method, while there was no clear and statistically significant pattern across other demographics. The participants' concerns showed that a possible implementation of new tolling methods requires transportation institutions and professionals to educate public about congestion pricing, and the new tolling methods to overcome possible public opposition.

The estimated choice models showed that toll selection behavior of participants is affected by toll rate, travel time savings, and participants' income level, and commuter status. Count-down toll clock seemed significant in decision-making process of the participants in the introduced method, and considered to be analyzed further in future studies. Statistical simulation study showed that the introduced method greatly increases the total revenue generated through tolling, and improves the capacity utilization of the toll road as compared to the results under fixed tolls. The number bid levels is an important parameter of the descending price auction as it is increased the total revenue also increases but at a decreasing rate. Moreover, the introduced method may not after all create a major transportation equity concern, as the two income groups with different levels of disposable income were accepted to toll road by toll operator at a similar ratio. However, additional research is needed to further study the impacts on low income groups since in this study only two broad income groups (those with less or more than $50K) are considered and modeled due to the size of the sample. The simulation results also showed that the total toll revenue increases at a decreasing rate as the number of bid levels is increased.

2.7.2 Future Recommendations

Although the results presented here seem supportive of future tolling methods, there are several study limitations. First, the current study is limited to the respondents residing in Virginia; more data collected among other states would be beneficial to better understand public perception. Collected data were biased towards high income respondents with a high level of education; while survey penetration to low income respondents and elderly was an issue. These penetration issues may stem from differences in technology use across generation, or limited access to survey means such as the availability of internet or personal computer for particular population groups. These obstacles should be overcome in a future study.

In the proposed auction system, it is envisioned that fully automated and connected vehicle environment is provided to the drivers; therefore, the driver distraction is not considered as an obstacle. In this system, toll operator's offer may be accepted by either the driver with a simple answer of yes or no through voice message, or through certain built-in buttons in the car. On the other hand, it is also possible that a programmable interface within the vehicle, in which information regarding the trip purpose, toll budget etc. are entered by the driver, may also somewhat automate and communicate the decision and give route-guidance.

In the survey, only commuting to work or school was considered as trip purpose, and the public response to the effect of late arrival or early arrival, and the effect of unexpected congestion on decisions were not tested since they were found to be beyond the scope of the study. Also, the proposed system over the survey is not an actual auction, and does try to mimic the actual implementation to understand how public would react to new pricing methods. Therefore, the exact behavior caused by competition is not captured by this study, while the real effect of count-down toll clock speed, which was omitted from the choice model estimation, should be investigated further. To understand the effect of those, a lab experiment with driver-subjects may be conducted, or an online auction game with a number of driver-subjects can be conducted in order to eliminate the effect of pressure or excitement formed in a lab setting.

3.0 GAME-BASED SURVEY: COMPARING VOT DISTRIBUTIONS

To accomplish Tasks 1 and 2 of the project, the ODU research team also designed a game-based survey implemented with students in graduate and undergraduate classrooms in a variety of departments at Old Dominion University. The game required the students to watch a series of short videos and identified preferred toll prices for each scenario. This section describes the background, survey methodology, and findings from the collected data. An extended version of this section was submitted as a paper to the Transportation Research Board 2017 Annual Conference, and presented in a poster session.

3.1 BACKGROUND

Revolutionary technologies now being introduced in automotive transportation, such as Vehicle-to-Infrastructure (V2I) and Vehicle-to-Vehicle (V2V) communications and autonomous (or semiautonomous) vehicles, suggest a great potential for the future. These technologies are revolutionary because they open up a completely new era of possibilities for car journeys. One such possibility is freeing drivers sufficiently to allow participation in auctions for access to toll roads. However, researchers must investigate these future scenarios without the benefit of historical or empirical data, a situation that leads to assumptions about future scenarios based on a current environment that might not be reflective of the future environment. These assumptions might be technology based, like acceleration rates of cars, or they might be related to the decisions that humans make, like whether to use a toll road.

To achieve an efficient distribution of traffic over the tolled and general-purpose lanes or roads, the toll magnitudes need to be set carefully. Optimal setting of toll magnitudes would require a detailed knowledge of the population being served. Understanding individual Values of Time (VOT, sometimes alternatively called value of time saved) allows estimating the utility each driver assesses to determine the utility of using a toll road. It is expected that with the emergence of connected and automated vehicles, more sophisticated tolling mechanisms, such as auctions, would be employed in the future. This research shows, from survey data, that individual VOT may vary depending on the tolling mechanism being used, especially for auction mechanisms. The auction methods considered in this research are a Sealed-bid auction and a Vickrey auction. Both mechanisms assume a sufficiently advanced technology is in place for them to be deployed, i.e., Vehicle-to-Infrastructure (V2I) communication. The results indicate that there is a difference in the VOT estimates for both auction types and this difference can be explained using Auction Theory.

It has been suggested that tolling is the only feasible mechanism to generate the $3.14 trillion needed to repair and upgrade the U.S. interstates (Poole, 2014). Collecting tolls has become easier and more efficient due to technological advancements (e.g., E-ZPass® systems). These factors make tolling a promising area for research (Michalaka et al., 2011; Gardener et al., 2013). There are several existing mathematical models of auction mechanisms (Wie, 2007; Yang, 2008; Cheng and Ishak, 2013; Zhang et al., 2014). This paper addresses auction tolling which depends on bids made by travelers ("bidders") as opposed to fixed price tolling (which may vary at different points in the day) or varying toll prices based on some feedback mechanism (Zhang et al., 2008; Cheng and Ishak, 2013; Zhang et al., 2014). The toll operator must decide which bids to accept and what the underlying auction tolling mechanism is.

Others have looked at auction tolling, including Teodorovic et al., who proposed a bid entry systems for a downtown area, and Zhou and Saigal, who used a combinatorial auction approach (Teodorović et al., 2008; Zhou and Saigal, 2014),. The ODU research team has previously developed a simple toll-road scenario in Phase I of this project to investigate the use of a Vickrey auction for tolling (Collins et al., 2016). The scenario contained a single origin-destination pair that was accessible via a single general purpose (GP) road and a toll road. The modeled toll road permitted entry at the origin and at the midway point. As expected, the revenue and usage of the toll road depended heavily on the number of users and their VOT. The ODU research team followed up this work with an investigation into the impacts of using different VOT distributions with similar arithmetic means (Collins et al., 2015a). Three continuous probability distributions were considered, including beta distributions, log normal distributions, and triangular distributions. The results indicated that there was only a slight difference between the tolling revenues generated from these theoretical probability distributions.

In this chapter, we present some of the results from a game-based survey focused on evaluating the Value of Time (VOT) distributions for two different tolling auction types. Data were collected for three time-saving scenarios for each auction type. Our hypothesis was that different tolling mechanisms would result in different VOT distributions.

3.2 METHODOLOGY

To collect information about the participants' VOT estimates, a video survey approach was used. Since the proposed tolling mechanism requires future technology, revealed preferences of drivers could not be obtained and results rely on stated preferences obtained from the surveys. To add some realism to the surveys questions, the research team produced videos of a driver in a car prompted about tolling prices via a Heads-up Display (HUD) on the windshield. A still-frame from survey video is shown in Figure 9.

Figure 9: Video still-frame from the survey showing typical HUD message.

The participants were shown a series of videos, each from the driver's perspective. The car in the video is driving along a non-descript highway when a series of messages about an approaching toll road are projected on the windshield of the car. The video was used to (a) add some visual realism to the survey and (b) ensure the participants made their decisions within a limited time-frame. The video varied by both auction mechanic and time-savings gained. A list of scenarios considered in this paper is given in Table 8. The table shows the time the driver would require travelling on the general purpose (GP) road and the toll road, as well as the Travel Time Savings (TTS) of using the toll road. Different time-savings were used in each case to avoid participant bias from their previous answer. All scenarios used the same ratio of 1.5 between the GP and toll road travel times. For the Vickrey Auction, the participants were also shown the accepted bid cut off point. This cut-off point was based on a VOT of $10 per hour.

Table 8: The travel time savings (TTS) and prices offered for the video scenarios.

	Travel Time (mins)			
	GP	**Toll**	**TTS**	**Revealed Accepted Bid**
Sealed-bid	90	60	30	-
Sealed-bid	36	24	12	-
Sealed-bid	18	12	6	-
Vickrey	54	36	18	$3.00
Vickrey	39	26	13	$2.17
Vickrey	27	18	9	$1.50

Before viewing the videos, participants were asked to consider the same everyday real-world scenario for each video in the survey, such as travel to and from work, travel to visit friend, etc. This flexibility in scenario selection was to encourage the survey participants to make the survey relevant to them, as we assumed that a more relevant scenario would solicit more accurate responses.

Internal Review Board (IRB) approval was obtained for this survey to ensure we met the ethical requirements of proper research. No demographic information was collected from the participants to help reduce participant's bias. For example, if a participant knows they will be asked their ethnicity then they will feel that they are representing that ethnicity in the survey which might bias their answers (as we were interested in the individual answers and not what that individual thought their ethnicity would answer).

Most of the data collection occurred in a classroom setting. The purpose of the survey (to solicit VOT estimate) was not explained until after the participants had completed the survey. In each video, the same ordering of messages was displayed to the participants:

1. A warning of the approaching toll road
2. The travel-time via the GP and toll roads, along with TTS
3. A prompt for the participant's bid for the toll road (written on paper in the classroom)
4. Auction end notification

3.3 FINDINGS

The survey was completed mainly by students and instructors/professors at Old Dominion University, Norfolk, Virginia. A variety of different students participated in the survey: undergraduate/graduate, male/female, full-time/part-time, and of all adult age ranges. There were 151 participants in total, though 13 were removed due to misunderstanding by those participants (the participants were asked to mark an answer with a '*?*' if they were confused about what they were asked to do). Thus, the results presented here are from the 138 completed participant results. Three questions accompanied each scenario, resulting in 404 data points.

Figure 10 shows an empirical probability estimate for the three sets of Sealed-bid auction scenario. Figure 11 shows results for the Vickrey auction. The results shown are for the VOT per hour estimates for the different scenarios for comparison. Estimates were made by dividing the price offered by participants by the time-savings (in hours), e.g., a bid of $3.00 for a 20-minute time-saving would give a VOT estimate of $9.00.

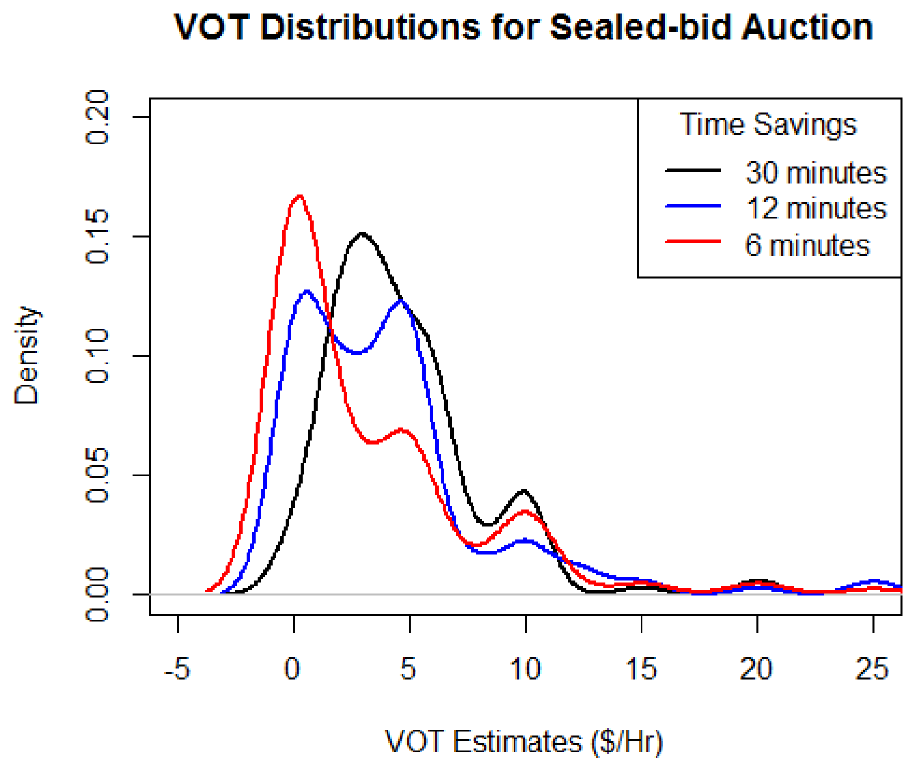


Figure 10: The empirical Probability Density Function (PDF) for the Sealed-bid Auction.

Figure 10 shows results from the three different Sealed-Bid scenarios with TTS: 6 mins, 12 mins, and 30 mins. An Analysis of Variance (ANOVA) was conducted to see if the three sets of results could be coming from the same underlying distributions (as the values have all been normalized to the *per hour* VOT). The ANOVA test had a p-value of 0.024, which implies that they are significantly different at the 95% confidence level. We see this difference in the mean values for the three scenarios: at TTS of 6 mins had a mean VOT estimate of $3.30 per hour, TTS of 12 mins had $4.01 per hour, TTS of 30 mins had $4.68 per hour, and the overall average for the Sealed-bid scenarios was $4.00 per hour. This implies that the VOT was not a constant value, but that as time-savings increased, VOT as reflected in bid amounts increases proportionally.

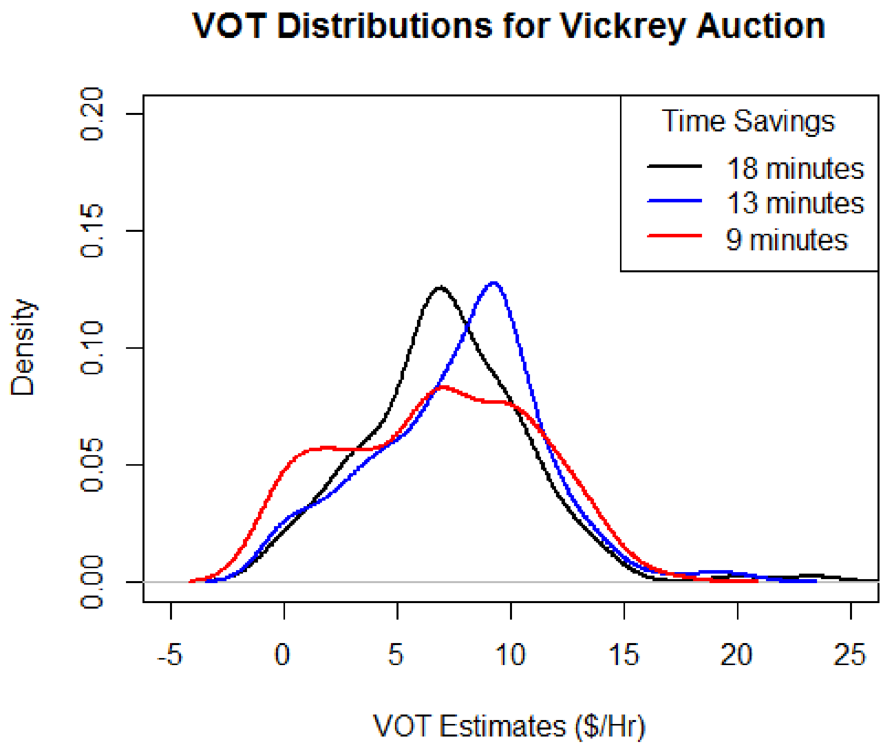


Figure 11: The empirical Probability Density Function (PDF) for the Vickrey Auction.

Figure 11 shows results from the three different Vickrey auction scenarios with TTS: 9 mins, 13 mins, and 18 mins. The ANOVA test did not show significant difference at the 95% confidence level with a p-value of 0.154. This implies that the results from the three cases come from the same distribution. At TTS of 9 mins had a mean VOT estimate of $6.65 per hour, TTS of 13 mins had $7.65 per hour, TTS of 18 mins had $7.12 per hour, and the overall average for the Sealed-bid scenarios was $7.18 per hour.

The average VOT for the Vickrey auctions was $7.18 per hour compared with $4.00 per hour for the Sealed-bid auctions. To understand this difference, we conducted a series of statistical tests at the 95% confidence level. The F-test for equality of variances was passed (p-value of 0.160) so the two samples were assumed to have similar variance for a one-way T-test. The tests failed at the 99% confidence level (p-value of 8.78E-28). It should be noted that the T-test assumes normality, which clearly is not the case (as you cannot have a VOT of less than zero).

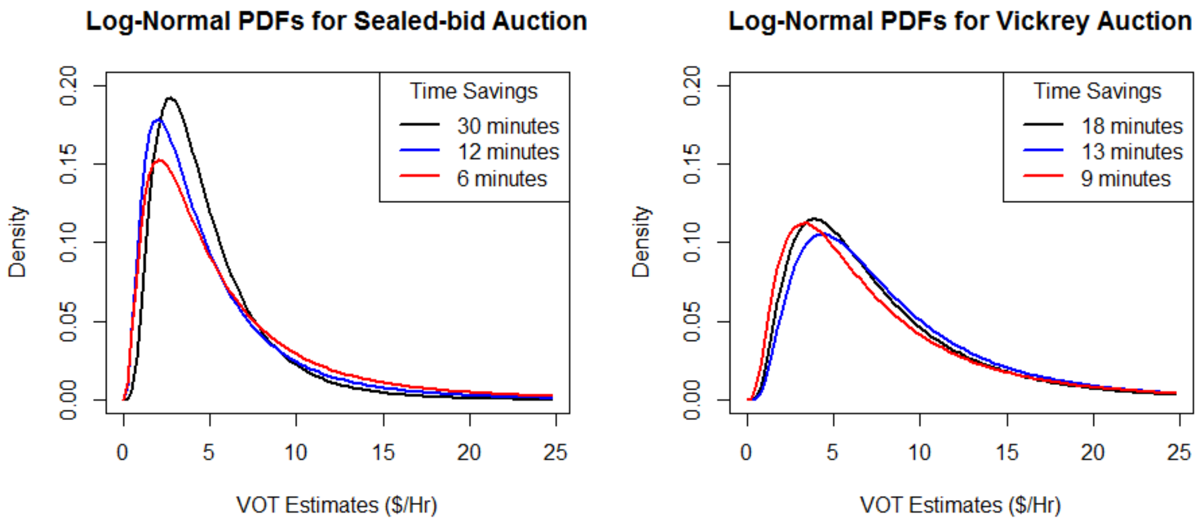


Figure 12: Smoothed log-normal estimate from the survey results.

To get a better understanding of the two sets of data, they were smoothed to fit a log-normal distribution. Figure 12 shows the graphs from this smoothing. From a visual inspection, the Vickrey Auction seems to produce a higher VOT estimate than the Seal-bid auction. The next question we ask is why?

3.4 DISCUSSION

Strictly speaking, our results show a distribution of bids and not a distribution of VOT because, according to Auction Theory (Krishna, 2009), bidders will not necessarily bid what they value something to be worth. This occurs because bidders seek to pay less for something than they believe it is worth. The size of the deviation between a bidder's bid from their VOT will depend on the auction mechanism (mechanism design). To understand how bidders deviate from their evaluation of an item requires a formal analysis using Game Theory. Maurice Vickrey, the father of the Vickrey Auction, was the first to formally analyze auctions using Game Theory techniques (Vickrey, 1961).

Vickrey showed that for a single-round, single item Vickrey auction (with the bidder's value of the item chosen from a uniform distribution), the best strategy was truthful bidding; that is, bidders should bid their actual valuation. In our case, this corresponds to drivers bidding the dollar amount that corresponds to the toll roads' time-savings multiplied by their Value of Time (VOT). The scenario for which Vickrey proved his theory differs from our scenario in that our auctions are a multi-identical item with incomplete information (the number of items is unknown by bidders). To the authors' knowledge, there currently does not exist a proof relating to this scenario. As such, we use Vickrey's scenario to inform our understanding of bidder's response, accepting that it is only an indicator and not a proof of bidder's normative strategy.

Vickrey considered a single-round, single item Sealed-bid auction with bidder's values drawn from a uniform distribution. In this case, the best strategy was:

$$\frac{n-1}{n}v \tag{5}$$

Where *n* is the number of bidders taking part and *v* is the bidder's actual value of the item. Thus the bidder will bid lower than their valuation of the item. Note that:

$$\frac{n-1}{n}v < v \quad \forall v, n > 0 \tag{6}$$

This shows that in a Sealed-bid auction, we would expect the bidders to bid lower than their valuation of the product. Thus, the average value of the bid in the Vickrey auction should be greater than that in Sealed-bid auction, which is implied from our results (as the VOT distribution is derived from the actual bids and the mean values are lower for the Sealed-bid case). The results obtained are in line with Auction Theory results.

As an exercise in curiosity, we decided to estimate the value of *n* from our results. Thus, if we assume the bidding formulas are correct, we can determine the average number of other bidders our participants were expecting per toll road space. We assume that the average for the Vickrey Auction is the actual average VOT. To obtain an average of $4.00 bid for the Sealed-auction, participants would have to assume somewhere between $n = 2$ ($3.59) and $n = 3$ ($4.79).

A final note is that according to Revenue Equivalence Theory (RET) the revenue generated by either the Sealed-bid or Vickrey auction should be the same for a same group of bidders (Myerson, 1981; Riley and Samuelson, 1981). However, RET is a normative result and does not reflect the descriptive reality.

3.5 CONCLUSIONS

This chapter presented results from a survey assessing two future auction tolling approaches: Sealed-bid and Vickrey. The motivation for the survey stemmed from previous concerns about which VOT distributions to use for auction tolling(Collins et al., 2015a). The survey involved participants viewing videos of several tolling scenarios and placing their bids for use the toll road. Three different travel time savings levels were considered for both auction mechanisms. The results indicated that there was a difference by participants between the bidding strategies for the two mechanisms, with participants bidding lower in the Sealed-bid auction. According to Auction Theory, this result was expected.

Auction tolling has advantages over other dynamic tolling approaches because its prices are an immediate reaction to the current demand and better capture the true willingness-to-pay of each traveler. However, there are many unresolved issues with auction tolling, e.g., whether the public will understand them in practice. This research is one step in understanding how the public will receive auction tolling. The previous section also addressed perception of tolling mechanisms to anticipate plausible implementation of these methods into real-word toll road planning.

4.0 INCORPORATING SURVEY FINDINGS INTO A MATHEMATICAL MODEL

This section provides an overview of the effort to incorporate the video survey results, given in Section 0, within the theoretical mathematical model that was developed in the first year of the project (Collins et al., 2015a; Collins et al., 2016). The model considered a future scenario where an auction was used for tolling; the drivers would bid to use the toll road before arriving at some decision point junction.

Changes in technology will allow for new mechanisms to conduct tolling. One such mechanism could be the use of auctions to determine who can access the toll road. The likely technology required for the use of auctions on roads includes Vehicle-to-Infrastructure (V2I) communication, so drivers can place their bids and be informed of successful bids. Additionally, driverless vehicles will facilitate this future approach to tolling by auctions, so that bidding will not be a distraction to driving. Another technology that will need to be derived is the algorithm for determining whom the toll-operators allow on the toll road, based on their bids. Our model used one such auction tolling mechanic, the Vickrey Auction, within a game theoretic framework to determine the optimal revenue that the auctioneer can achieve from the bids submitted.

The distribution of drivers' bids is based on our empirically derived VOT distribution, where drivers will bid an amount equal to their VOT multiplied by the time-savings. Drivers have perfect information; that is, they know exactly what the time-savings will be. The time-savings will vary depending on the number of cars moved from the general purpose (GP) road to the toll road. If the toll operator accepts too many cars on the toll road, then congestion will increase on it, making travel time longer (while simultaneously decreasing the travel time of the now less congested GP road). This will make the toll road less valuable to drivers and they will bid less. The toll operator (auctioneer) must decide on a balance between the number of cars paying tolls and their effect on the congestion of the toll road.

Allowing drivers to bid on access to the toll roads gives them greater freedom in determining the use of the service (toll road); it also allows for the toll operators to react in real-time to the changing demographic of drivers who will, potentially, have their own value of time.

The advance in technology also allows for new ways of conducting tolling to emerge. For example, tolls are usually paid for in series, one after the other, as drivers move from one toll road to the next. What if drivers could pay for a group of toll roads they intend to use that day at once? The scenario in our model considers two toll roads in series where the drivers can bid on continuous access to both toll roads or access to each individual toll road. The drivers are allowed to place bids in all three cases, and the tolling mechanism does not allow them to double pay (because their individual access and continuous access bids were accepted). This multiple toll road pricing is already in effect at a basic level in the real world; for example, the Chesapeake Bay Bridge Tunnel offers a discount for return trips within 24 hours (http://www.cbbt.com/).

Our approach was to take the analytical model, developed in the first year of the project, and inject real-world data into it. The purpose of doing this was to determine if more insights can be found from the model through further analysis of a real-world-like scenario. Details of the theoretical model can be found in Collins et al. (2016). The real-world scenario is taken from the Hampton Roads region of Virginia in the USA. Since the survey data was collected from the Hampton Roads area, it was appropriate to use data from toll roads in the region as well. Due to using an empirical VOT distribution, the model could not be solved analytically, requiring instead an exhaustive numerical approach.

4.1 SCENARIO

We developed the scenario using a combination of theoretical networks and real-world data. We use the same network as the one for the previous theoretical research into this problem (Collins et al., 2016). Figure 13 shows a node-arc diagram of the network under consideration. Three nodes are considered to allow for combinatorial bids, e.g., bidding on using the toll road from AC as well as AB. The real-world data used informs two parts of the model: the drivers VOT and the roadway characteristics. The survey data was used to generate a VOT distribution for the model. The roadway free-flow travel times and capacities were informed by actual road data, based on tolling and general-purpose roads in the Hampton Roads area.

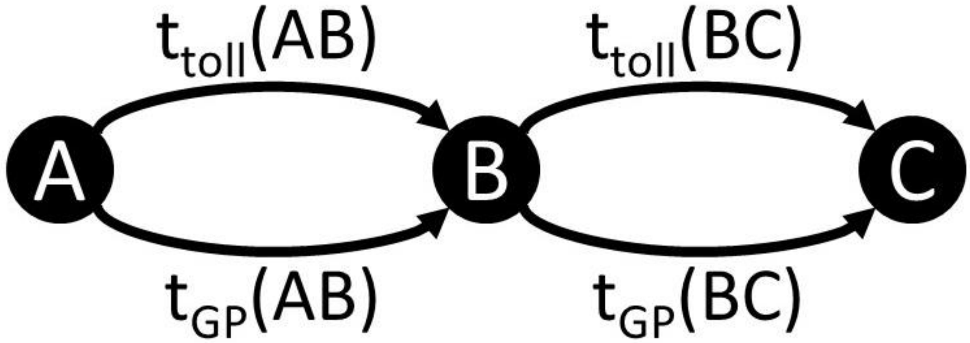


Figure 13: A node-arc diagram of the road networks used in research.

4.1.1 Network

The road network follows a simple structure that includes toll roads with combinatorial bids. All drivers are assumed to start at origin Node A, and they are traveling to destination node C via interchange node B. The drivers will either travel on a toll road or general purpose (GP) road, depending on the outcome of the toll road auction. The two toll roads are considered separate, and a driver may enter the BC toll road if their AC or BC bid was accepted. Those drivers whose AB bid was the only one accepted will transfer to the BC GP road at B. The authors assume that movement between the two roads at the intersection is smooth and does not interfere with the flow of traffic.

4.1.2 VOT Distribution

The VOT distribution is empirically derived from survey game results. Since the distribution was derived from 138 data points, the value of time was determined by the following function:

$$V(p) = \max_{i \in \{1,2,\ldots,138\}} \{u_{(i)}: i \leq \lceil 138p \rceil\}$$

Where *V(.)* is the minimum value of time for proportion p (>0) of the population. $\{u_{(i)}\}$ is the ordered list of game participants' value of time. The exact set of collected data values used for this VOT distribution was the result of the Vickrey auction with travel-time savings of nine minutes (which translates to a toll road travel time of 18 minutes and general-purpose road travel time of 27 minutes); this scenario was chosen because its value is close to the baseline scenario used in this analysis.

4.1.3 Roadway Characteristics

In the original theoretical model, all segments were identical in length and capacity. The values were normalized also thus giving little meaning to the output values (total revenue) other than being able to compare relative scale between two sets of results. To overcome these issues, real world data was used in the model. Since all the VOT data was collected from people living in the Hampton Roads of Virginia, USA, the real-world trips, used to collect the data, were drawn from that area.

The main trip considered was a trip from Old Dominion University's (ODU) main campus, in Norfolk, VA, to ODU's Virginia Modeling, Analysis and Simulation Center in Suffolk, VA. The authors' offices are located in these two locations, e.g., Dr Cetin is located in the main campus and Dr Collins is located at VMASC. Thus, the trip used is an actual one that the authors had to undertake on a regular basis. Though there are several toll roads in the Hampton Roads area, there does not exist a trip that completely replicated the ABC network given above. The data used to inform the network was drawn from multiple possible paths; each scenario was made up of a path with a toll and a non-tolled alternative.

A list of considered paths is given in the Table 9, each is given an abbreviated name. The paths from ODU to VMASC are label east and the reverse is label west. The analytical model requires both Free-Flow Travel-time (FFTT) and roadway capacity. We calculated these values for each path using the approaches discussed below.

Table 9: Characteristics of trips from ODU main campus to VMASC.

Name	Direction	Toll	Free Flow Travel Time (mins)	Distance (miles)	Capacity (vh/hr)
MTT	East	Yes	17	9.9	1000
MTT	West	Yes	18	10.1	1000
JB	East	Yes	37	18.5	300
JB	West	Yes	39	19.1	300
DTT1	East	Yes	32	14.9	400
DTT1	West	Yes	31	14.9	400
DTT2	East	Yes	33	20.2	600
DTT2	West	Yes	33	20.4	600

GP	East	Yes	40	26.5	600
GP	West	Yes	40	27.5	600
CHTOLL	East	Yes	7	6.5	4000
CHTOLL	West	Yes	7	6.8	4000
CHGP	East	Yes	10	7	300
CHGP	West	Yes	10	6.5	300

4.1.4 Path Selection

We wanted a cross section of different paths for our analysis. Thus, a selection of different tolled routes was chosen which reflect all the major tolled crossings from Norfolk to Portsmouth over the Elizabeth river. These crossing include the Midtown Tunnel (DTT), Downtown Tunnel (DTT), South Norfolk Jordan bridge (JB). In all these cases, we chose the quickest free flow travel for these paths between ODU and VMASC that went via that crossing. To add some further variation to the analytical results, we also included a second slower path that goes through the DTT, which had higher capacity than the first; thus, the DTT paths are label DTT1 and DTT2. These tolling paths are shown in **Error! Reference source not found.**. The Chesapeake Expressway (CH) will be discussed later in this section.

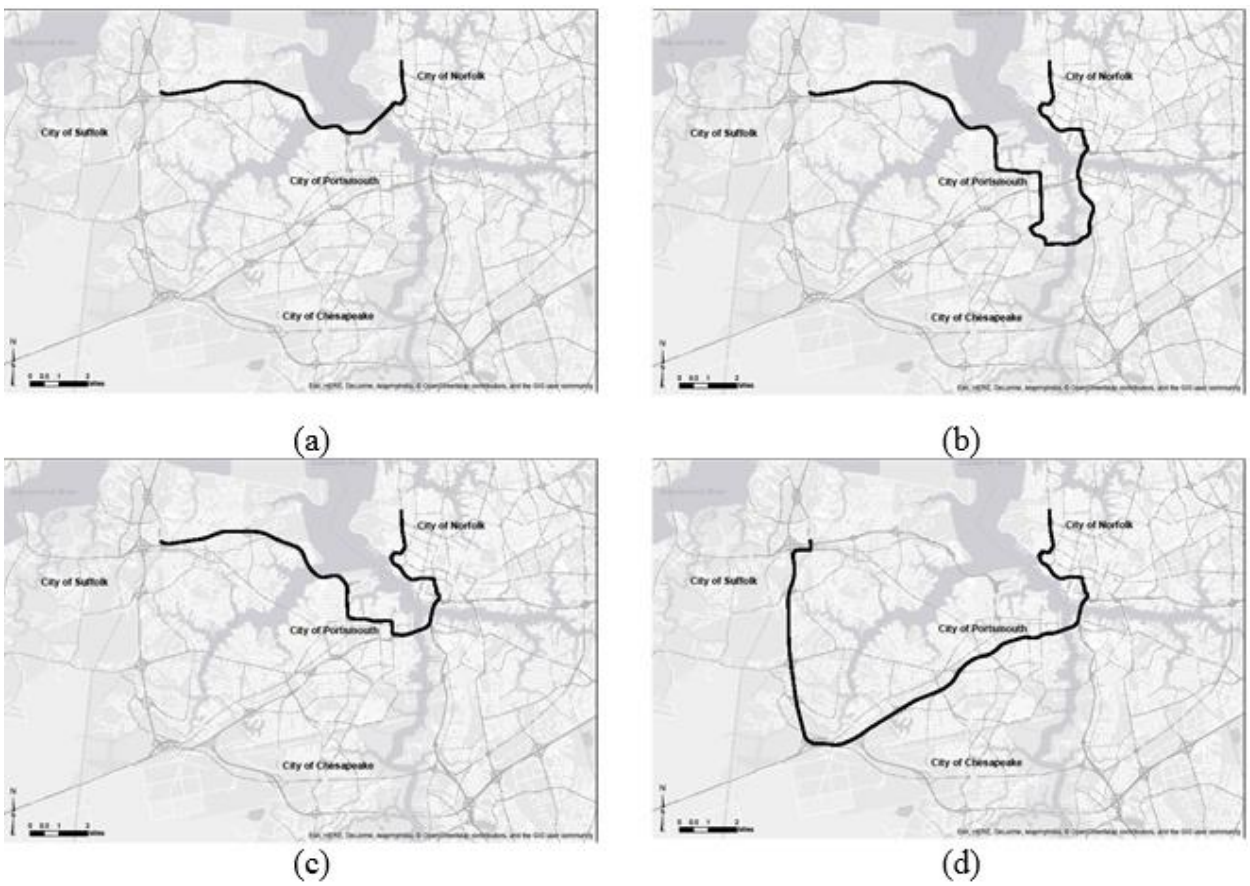


Figure 14: Maps showing the four tolling paths between ODU and VMASC over the Elizabeth River: (a) MTT, (b) JB, (c) DTT1 and (d) DTT2.

The MTT provides the fastest route to VMASC via the Western freeway (VA Highway 164), its toll prices are $1.50 during peak period as of 2016 (www.driveert.com/toll-info/toll-rates/). The DTT1 path also uses the Western Freeway but the route is longer due to the diversion needed to reach the Downtown Tunnel. The second Downtown path, DTT2, uses the interstates I-64 and I-664 which results in a longer path but at higher roadway speeds. The Downtown tunnel uses the same pricing structure as the Midtown Tunnel. The JB path diverts the traveler even further, to get back to the Western freeway, thus the longest travel time of tolled paths but still quicker than the non-tolled path. The Jordan Bridge has a slightly higher toll rate of $2.00 (www.snjb.net), which reflects the demand to and from the Norfolk Naval Shipyard. The Commonwealth of Virginia introduced all these toll prices in 2014 and there has been much controversy around them.

We choose a single non-toll general-purpose (GP) path as the baseline for analysis. All the toll roads have a faster travel-time than the GP path, as expected, but the capacity could be lower, higher or equal to the capacity of the GP path. Thus, these real-world paths allow for varied combinations of tolled path and GP path to be used in the analysis. The GP path uses interstates (I-464 and I-64) but is still must cross the Elizabeth River via the non-tolled Highrise bridge. The figure below shows the route for the GP path.

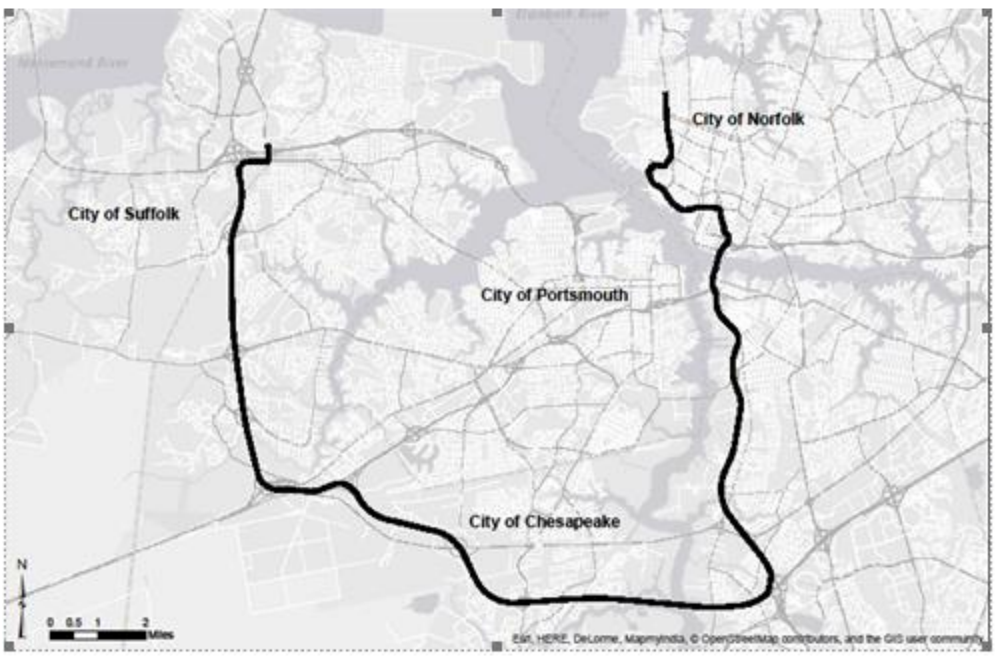


Figure 15: A map showing the General Purpose baseline path between ODU and VMASC.

The path travel times are in the range of 17 minutes to 40 minutes. The project team wished to include another path pair (tolled and non-tolled) that had a much lower travel time estimates but still based on a real-world example. There are two other tolls in the Hampton Roads area, beyond those already discussed, namely: Chesapeake Expressway and Chesapeake Bay Bridge-Tunnel.

Unfortunately, there is no reasonable journey that passes through either toll when travelling from ODU to VMASC.
The Chesapeake Expressway is part of the connections between Hampton Roads and North Carolina border. We developed a new path pair for the Chesapeake Expressway, which started at the last exit before the toll road and ended at a junction after the toll road ends. This resulted in travel times of 7 minutes and 10 minutes for the tolled and GP paths respectively. The paths are shown on the maps found in **Error! Reference source not found.**.

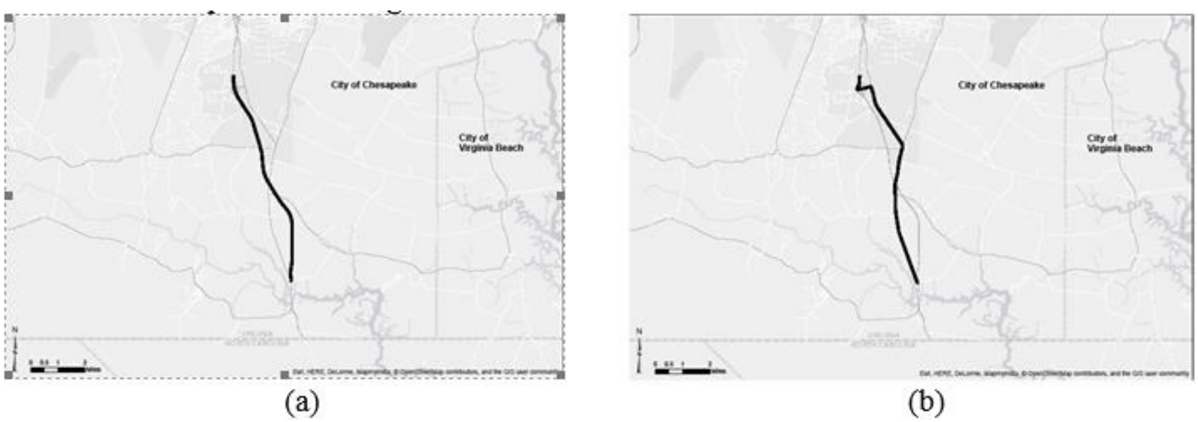


Figure 16: A map showing the (a) tolled and (b) General Purpose paths for the Chesapeake Expressway.

Chesapeake Bay bridge tunnel was not used in this analysis due to the extreme differences it makes for reaching locations on Virginia's Eastern Shore (the alternative is to drive via Washington, D.C.) thus was felt might skew the results when comparing a 50-minute journey to a 7-hour non-tolled journey.

4.1.5 Determining Travel Times

The free-flow travel time for the paths was determine using the travel-times obtained from Google maps. We calculated the travel time expected at 4am on a weekday (not Friday). Since this time was outside of any rush hour traffic or other major disturbance, we assumed it was the free flow travel time for the path. This estimate might be slightly under the actual free-flow travel times due to difference in driving at 4am, e.g., people drive slower in night conditions.

4.1.6 Determining Capacity

Each of the paths used multiple facilities and, in many cases, included signalized junctions. To determine the capacity of the paths, we used the lowest capacity point of the path to determine the overall capacity. The logic behind this choice was that the capacity of the path, assuming no cars left it or others joined, was, at most, the capacity of its lowest capacity point.
The parts of the ODU to VMASC paths which overlap for all the paths was ignored for determining the lowest capacity point otherwise most to paths considered would have the same capacity and thus fail to produce diverse results. The roads ignored were Hampton Roads, Norfolk, where ODU is located, and University Blvd, Suffolk, where VMASC is located. The table below summaries the choke points of the paths.

Table 10: Tolled roadway descriptions in Hampton Roads, Virginia.

Name	Direction	Location	Capacity (vh/hr)
MTT	Both	Single lane just before/after the midtown tunnel	1000
JB	West	Single lane with straight on stopping at four-way light (Elm Ave. and Portsmouth Blvd.)	300
DTT1	Both	Single lane going into yield (Bart St. going into Effingham St., Portsmouth)	400
DTT2	Both	Two lane straight on stopping at four-way traffic light (various points on Brambleton Ave.)	600
GP	Both	Two lane straight on stopping at four-way traffic light (various points on Brambleton Ave.)	600
CHTOLL	Both	Two-lane expressway	4000
CHGP	Both	left on four-way signal intersection from single lane slip road to two-lane divided town road (from Chesapeake Expressway junction 8 to Hillcrest Rd.)	300

4.2 MATHEMATICAL PROGRAM

The purpose of this sections research is to use real-world data in the mathematical program of an auction tolling situation presented in Collins et al. (2016). A direct insertion of the data is not possible due to the difference between the original theoretical data used and the real-world data, i.e., the empirical VOT distribution is discrete whereas the theoretical distributions were continuous. This section presents equations used in the theoretical scenario and adapts them for use with the empirical data. The equations that need to be discussed are the link travel time function, the bidding equations of users, and the mathematical program to maximize the toll operator's revenue.

4.2.1 Link Travel Time Function

We only have data on free-flow travel times for the paths presented above. We, therefore, have to make estimates on the travel-times in non-free-flow conductions. In the original theoretical model, this was done using the Bureau of Public Roads (BPR) standard equation for congestion on road segments, shown in Equation (1), the use of which is also supported by Teodorović et al. (2008). This equation is based on Greenshield's "fundamental diagram of traffic flow" (Greenshields, 1935).

$$t(l, v(l)) = t_{ff}(l)\left(1 + 0.15\left(\frac{v(l)}{c(l)}\right)^4\right) \quad (7)$$

This equation determines the travel time t of a link l for a traffic volume v for a given free-flow travel time t_{ff}, and the road segment capacity c.

4.2.2 Bidding Mechanism

There are two decision-makers in this system: the travelers and the toll operator. The equations below represent the decisions of the travelers. Based on individual VOT, the travelers will place bids for access to toll road segments. We assume that travelers have perfect knowledge about travel time on the road segments and are thus able to determine the travel time savings of using the toll road. The justification for this perfect knowledge is the assumption that regularly commuting travelers along the road would likely be able to make accurate estimates of travel time based on the current conditions. By using a Vickrey auction mechanism, the travelers lack incentive to bid anything other than their true estimates of the toll price. Based on these assumptions, a bidding formula for the travelers for arc AB is given below:

$$\mathrm{b}(\mathrm{AB},\mathrm{x}) = \mathrm{u}(\mathrm{x})\big(\mathrm{t}\big(\mathrm{AB}_{\mathrm{GP}},\mathrm{v}(\mathrm{AB}_{\mathrm{GP}})\big) - \mathrm{t}(\mathrm{AB}_{\mathrm{toll}},\mathrm{v}(\mathrm{AB}_{\mathrm{toll}}))\big) \tag{8}$$

A bid b of traveler x is determined by multiplying their value of time u by the travel time savings between the general-purpose and toll lanes. The advantage of using this bidding equation is that it stops the outcome where the toll operator just accepts all bids (this situation would make the toll road's congestion worse than the GP lane, leading the travelers to bid zero). A variation of equation (2) can also be used for bids of the *BC* road segment. Determining bids for using the toll road all the way from *A* to *C* (b(AC)) is trickier because it involves multiple road segments (equation (9)). We assume that this bid only considers travel time savings, which means that it relates to equation (2).

$$\mathrm{b}(\mathrm{AC},\mathrm{x}) = \mathrm{b}(\mathrm{AB},\mathrm{x}) + \mathrm{b}(\mathrm{BC},\mathrm{x}) \tag{9}$$

We assume that the toll operator takes the highest bids available for each segment. We also assume that the operator prefers bids for b(AC) over b(AB), as more guaranteed revenue is generated. Based on these assumptions, Collins et al. (2016) developed the following optimization problem:

$$\begin{aligned} \max_{\theta,\mu,\lambda\in[0,1]} \int_{F^{-1}(1-\lambda)}^{\infty} & \mathrm{b}\big(\mathrm{AC},\mathrm{F}^{-1}(1-\lambda)\big)\mathrm{f}(\mathrm{x})\mathrm{dx} \\ & + \int_{F^{-1}(1-(\theta+\lambda))}^{F^{-1}(1-\lambda)} \mathrm{b}\left(\mathrm{AB},\mathrm{F}^{-1}\big(1-(\theta+\lambda)\big)\right)\mathrm{f}(\mathrm{x})\mathrm{dx} \\ & + \int_{F^{-1}(1-(\mu+\lambda))}^{F^{-1}(1-\lambda)} \mathrm{b}\left(\mathrm{BC},\mathrm{F}^{-1}\big(1-(\mu+\lambda)\big)\right)\mathrm{f}(\mathrm{x})\mathrm{dx} \end{aligned} \tag{10}$$

Such that

$$\theta + \lambda \leq 1$$

$$\mu + \lambda \leq 1$$

The proportion of travelers that have their b(AC) accepted is λ, the b(AB) accepted is θ, and the b(BC) accepted is μ. The functions F and f are the cumulative distribution function (CDF) and probability distribution function (PDF) of the theoretical VOT distribution respectively. In the original paper, we assumed the VOT distribution was a triangular distribution. The three integrals show the total revenue generated from the three groups: those accepted for travel on the complete toll road and those accepted for travel on only one of the two segments. Since a Vickrey auction was the underlying mechanism for our scenario, all travelers that were accepted pay the same toll (which is the lowest bid of the ones accepted). For our empirical distribution, the mathematical program can be adapted to the following:

$$\begin{aligned}
\max_{\theta,\mu,\lambda\in[0,1]} \max_{i\in\{1,2,\ldots,138\}} (\lceil\lambda N\rceil \{u_{(i)}: i \\
&\leq \lceil 138(1-\lambda)\rceil\} \big((t(AB_{GP}, N - \lceil(\lambda+\mu)N\rceil) - t(AB_{toll}, \lceil(\lambda+\mu)N\rceil)) \\
&+ (t(BC_{GP}, N - \lceil(\lambda+\theta)N\rceil) - t(BC_{toll}, \lceil(\lambda+\theta)N\rceil))\big)) \\
&+ \max_{j\in\{1,2,\ldots,138\}} (\lceil\mu N\rceil \{u_{(j)}: j \leq \lceil 138(1-\lambda-\mu)\rceil\} (t(AB_{GP}, N - \lceil(\lambda+\mu)N\rceil) \\
&- t(AB_{toll}, \lceil(\lambda+\mu)N\rceil))) \\
&+ \max_{k\in\{1,2,\ldots,138\}} (\lceil\theta N\rceil \{u_{(k)}: k \leq \lceil 138(1-\lambda-\theta)\rceil\} (t(BC_{GP}, N - \lceil(\lambda+\mu)N\rceil) \\
&- t(BC_{toll}, \lceil(\lambda+\mu)N\rceil)))
\end{aligned}$$

Such that

$$\theta + \lambda < 1$$
$$\mu + \lambda < 1$$

The mathematical programming formulation removes the integrals since a discrete number of drivers are considered. Of the N bidders, proportions are accepted on the toll road, e.g, $\lceil \lambda N \rceil$, which are round to an integer value (since only whole bidder can use the toll road). The mathematical programming uses nested maximization; the next maximums come from the value of time function for the discrete case *V(.)*. As with the original mathematical program, it can be split up into three parts, which reflect the three accepted bidder groups.

4.3 COMPUTATIONAL RUNS

There are only three decision variables in the model: λ, μ, and σ. These represent the proportion of acceptance bids for the three types of bids: B(AC), B(AB), and B(BC). As with the previous iterations of the model, the objective was to maximize the total revenue generated from the toll bids. Due to the non-linear nature of the mathematical programming formulation, there was no obvious optimization strategy for the continuous case. However, since there will be a finite number of vehicles using the facilities there can only be finite number of vehicles that will be allowed on the toll road. As such, we can conduct a discrete exhaustive search. The increments of the search will be 1/N and there will be $O(N^3)$ possible cases to consider.

The proportions of acceptance determine both the travel-time savings and the VOT value used in determining the accepted bid (and, therefore, the price for using the toll road for a given time saving). If N >> 138 there will be lot of repeats of this search in the VOT values drawn from the empirical distribution (which only has 138 possibilities); however, since the proportions vary the total revenue will vary as well.

We considered each combination of trips for the AB and BC journey including repeats; leading to 15 complete scenarios from the five trip pairs (toll and GP roads). The demand was also varied, using the following nine rates: 200, 400, 600, 800, 1000, 2000, 300, 4000, 5000. Thus, there was a total of 135 scenarios considered. The exhaustive search program was written in Microsoft's Visual Basic for Applications and run on computers with i-7 quad core processes and 8 GB ram. The runs took approximately a day to complete.

A verification test was completed on the computer model by comparing it to the theoretical scenario used in previous work on analyzing Vickrey auction tolls (Collins et al., 2016). In this case, the travel time, capacity, and demand where all set to one. The scenario was not completely the same as previous model produced in Matlab because our approach used a empirically informed VOT distribution. The results for the (λ, μ, σ) triple were (8.0%, 8.7%, 8.7%) and a revenue of \$0.005 from our model and (7.6%, 9.5%, 9.5%) and a revenue of \$0.018 from theoretical model. Those the numbers are different they do follow the rough same order of magnitude (7-10%) on acceptance on the toll road and have similar characteristics. For example, the numbers of AB bids accepted was equal to the number of BC bids, and both were slighter greater than the AC bids accepted. The difference revenue generated is most likely caused by the different in the empirical VOT distribution (approximately log normal) and the theoretical one (triangular). Other distribution have been applied to the theoretical model (Collins et al., 2015a) and the results were as follows: log Normal (6.0%, 10.0%, 10.0%) and a revenue of \$0.018 and the beta distribution (7.7%, 9.6%, 9.6%) and a revenue of \$0.018.

4.4 ANALYSIS

The data runs generated the 135 sets of results as expected and will be discussed in this section. There were a couple of anomalies that we will discuss: the relationship between the number accepted on the toll road and demand. Finally, we will present general findings through linear regression models.

The Pearson's product-moment correlation between demand and natural logarithm of total revenue/hr was 97.4% (with a p-value of 2.2e-16), which means a very high correlation between the two variables. Thus, we conclude there is exponential growth in revenue with demand. This occurs due to the nature of the travel time function where increased demand will create a non-linear increase in the travel-time on the GP road.

The demand also had a profound effect on the percentage accepted on the toll road. For a very low demand of 200 / hr, there is no variation between the scenarios. In this case, 34.00% accepted for AC toll road travel and 28.00% of the other two cases (AB and BC). This means that 64% were accepted on the toll road. This high percentage occurs due to the travel time savings enjoyed the toll road user, even with a high proportion of traffic on the toll road. Variation between scenarios only occurs between a demand of 400 to 1000 per hour. The results from a very low demand can be seen as the case where the demand does not really impact the roads travel-time savings, so the toll operator is just maximizing the minimum accepted bid multiplied by number of accepted bids.

All 15 of the 2000 demand scenarios produced the same results. That was 7.95% accepted AC bids and 8.70% of the other two cases. This mean that only 16.5% (or one-sixth) of traveler got to use the toll road. These results were almost identical to the results when using demand of 3000, 4000, and 5000. The minor differences in results were due to the rounding errors, for example, 7.95% is exactly 159/2000 and 7.96% is exactly 398/5000. Obviously, the total revenue was different in each case due to the exact congestion conditions of any given scenario. The table below gives a complete list of results.

Table 11: Bid acceptance rates for high demand scenarios.

Demand	AC Bid Acceptance	AB Bid Acceptance	BC Bid Acceptance
2000	7.95%	8.70%	8.70%
3000	7.97%	8.70%	8.70%
4000	7.95%	8.70%	8.70%
5000	7.96%	8.70%	8.70%

The similarities of the results due to high demand are due to the overwhelming impact that demand has on the capacity of the paths considered. There is effectively gridlock created on the GP roads, which take many hours (or days) to clear. As such, the accepted bid prices range from $351 to $15,492. Drivers could find alternative paths than the one offered by the GP path and, thus, their bids would be much lower. Given this problem and the similarity of the results, we exclude all the scenarios with demand greater than or equal to 3,000 from our analysis. This reduced the number of scenario results considered to 90.

There is a correlation on -64.7% (with a p-value of 2.2e-16) between demand and percentage bids accepted. After removing scenarios of more than 2000 demand, this correlation only slightly increases to -69.4% (with a p-value of 3.4e-14) indicating is not just issues with high demand scenario that is causing a lower than expected correlation value. Thus, we include more characteristics of the roads, beyond demand, in the following analysis.

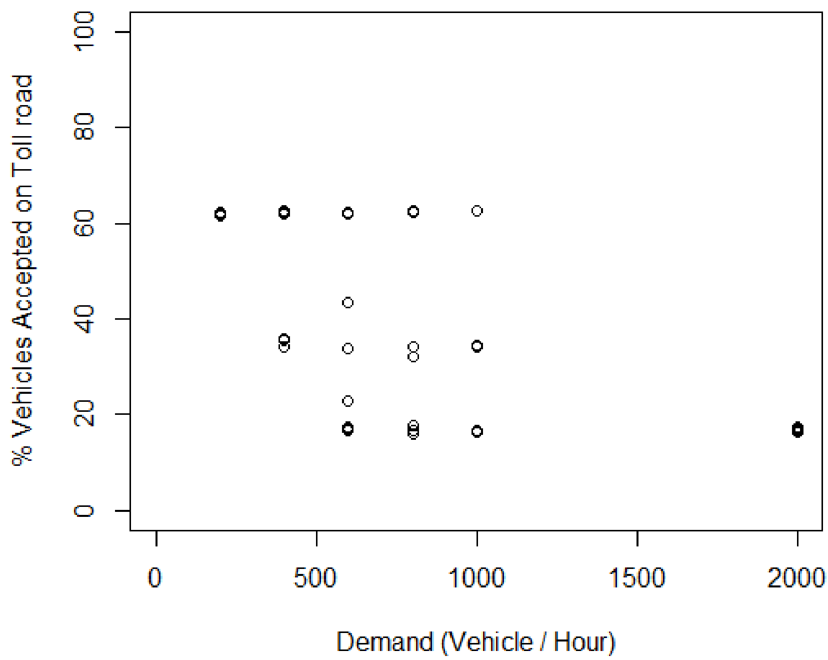


Figure 17: Fuzzed scatterplot of the percentage bidders accepted on the AB toll road as demand varies.

The correlations were found between the key output variables and some of the roadway characteristics. The output variables considered were the revenue generated and the proportion of drivers that used toll roads: AB_{toll} (AB_{use}) or BC_{toll} (BC_{use}). The input variables considered were the Demand (D), and the ratio between the roadway capacity and the demand ($AB_{GPRatio}$ and $BC_{GPRatio}$ respectively). The results from this investigation are given in the table below.

Table 12: Pearson's correlation statistics between input and output.

	AB_{TTS}	BC_{TTS}	$AB_{GPRatio}$	$BC_{GPRatio}$	Demand
AB_{use}	0.42***	0.10	0.70***	0.64***	-0.69***
BC_{use}	0.12	0.30**	0.73***	0.71***	-0.72***
Revenue	-0.02	-0.10	-0.39***	-0.38***	0.77***

** Significant at 95% level, *** Significant at 99% level

To test is there was any significant relationship between a single output variable and multiple input variables; multiple linear regression models were conducted. There was a 92% correlation found between $AB_{GPRatio}$ and $BC_{GPRatio}$ so we did not place them as inputs in the same regression models due to the requirement that input variables are independent. Two regression models are discussed which look at the proportion of drivers that could use the toll roads. The first model looks at the AB toll road.

$$AB_{use} = 0.31 + 0.01\ AB_{TTS} + 0.09\ AB_{GPRatio} - 0.0001\ Demand$$

All values were significant at 99.9% level. Approximately 71.3% of the variation of in AB_{use} could be explained with this model (from the adjusted R-square value). What this shows up that the faster the toll road is then more people will be allowed to use it by the toll operator. This is also true for a higher the capacity of the toll road. As with the previous results, the higher the demand the less people are able to use the toll road. A similar story was found for the BC toll.

$$BC_{use} = 0.39 + 0.01\ BC_{TTS} + 0.08\ BC_{GPRatio} - 0.0001\ Demand$$

All values were significant at 99.9% level and the adjusted R-squared was 65.1%. The difference between the models is due to scenarios considered (we did not consider both possible combinations for two paths when constructing the scenario list, e.g., we only considered the midtown tunnel path as the AB road).

The final statistics that we look are the accepted bid prices under different demand scenarios. A list of the average accepted bids can be found in Table 13. The table indicates that for low demand levels, the bids accepted are like those already used in Hampton Road tolls (approximately $1 - $2). This, of course, brings into question the usefulness of biding if the bid level just remains the same as in the existing toll price case. Note the due to the complex non-linear behavior of our tolling system the prices do not increase in a linear manner. However, as previous discussed, the total revenue is positively correlated to total demand.

Table 13: Average values from the different scenarios based on demand.

	Accepted Bid			Numbers Expected		
Demand	AC	AB	BC	AC	AB	BC
200	$2.82	$1.03	$0.85	68	56	56
400	$2.79	$1.05	$0.84	131	82	110
600	$4.06	$1.46	$1.63	132	112	112
800	$7.69	$2.50	$3.84	129	145	117
1000	$17.98	$5.90	$9.54	98	133	110
2000	$256.99	$84.58	$140.29	159	174	174

4.5 RESULTS

We found that when applying real-world data to our tolling mechanism the following were observed. When demand is high, the toll operator will only accept a small proportion of bidders onto the toll road and, when the demand is low, the toll operator accepts a high proportion of bidders. Thus, when demand is high the overall social welfare is low under this system, which may not be desirable to policy makers. It should be noted that even though the proportions are low for high demand, the toll operator will still accept more bidders onto the toll road than when the demand is low, e.g., when demand is 2000 about 333 bidders will use the toll road but only 124 will use it when the demand is 200.

5.0 REFERENCES

Adler, J. L. & Cetin, M. 2001. A direct redistribution model of congestion pricing. *Transportation Research Part B: Methodological,* 35**,** 447-460. http://dx.doi.org/10.1016/S0191-2615(00)00003-5.

Ausubel, L. M. 2004. An efficient ascending-bid auction for multiple objects. *The American Economic Review,* 94**,** 1452-1475. http://www.jstor.org/stable/3592830.

Bansal, P. & Kockelman, K. M. 2016. Forecasting Americans' Long-Term Adoption of Connected and Autonomous Vehicle Technologies.In *Transportation Research Board 95th Annual Meeting* (No.16-1871).

Bhat, C. R. 2003. Simulation estimation of mixed discrete choice models using randomized and scrambled Halton sequences. *Transportation Research Part B: Methodological,* 37**,** 837-855. http://dx.doi.org/10.1016/S0191-2615(02)00090-5.

Brownstone, D., Ghosh, A., Golob, T. F., Kazimi, C. & Van Amelsfort, D. 2003. Drivers' willingness-to-pay to reduce travel time: evidence from the San Diego I-15 congestion pricing project. *Transportation Research Part A: Policy and Practice,* 37**,** 373-387. https://doi.org/10.1016/S0965-8564(02)00021-6.

Burris, M., Nelson, S., Kelly, P., Gupta, P. & Cho, Y. 2012. Willingness to Pay for High-Occupancy Toll Lanes: Empirical Analysis from I-15 and I-394. *Transportation Research Record: Journal of the Transportation Research Board***,** 47-55. https://doi.org/10.3141/2297-06.

Carlino, D., Boyles, S. D. & Stone, P. 2013. Auction-based autonomous intersection management.In *Intelligent Transportation Systems-(ITSC), 2013 16th International IEEE Conference on*.

Cheng, D. & Ishak, S. July 31 2013. A Dynamic Feedback-Control Toll Pricing Methodology 1 for Revenue Maximization: A Case Study on I-95 Managed 2 Lanes.In *92nd Transportation Research Board Annual Meeting Washington, D.C.*

Collins, A. J., Frydenlund, E., Robinson, R. M. & Cetin, M. January 10-14 2015a. Comparing Value of Time Distributions in a Tolling Auction Mechanism Enabled by Vehicle-To-Infrastructure Technology.In *95th Transportation Research Board Annual Meeting Washington, DC*.

Collins, A. J., Frydenlund, E., Robinson, R. M. & Cetin, M. 2015b. Exploring a Toll Auction Mechanic Enabled By Vehicle-To-Infrastructure Technology.In *94th Transportation Research Board Annual Meeting Washington, D.C.* (No.15-2825).

Collins, A. J., Frydenlund, E., Robinson, R. M. & Cetin, M. January 11-15 2015c. Exploring a Toll Auction Mechanic Enabled By Vehicle-To-Infrastructure Technology.In *94th Transportation Research Board Annual Meeting Washington, D.C.* https://doi.org/10.3141/2530-13.

Collins, A. J., Frydenlund, E., Robinson, R. M. & Cetin, M. 2016. Exploring a Toll Auction Mechanic Enabled By Vehicle-To-Infrastructure Technology. *Transportation Research Record: Journal of the Transportation Research Board,* 2530**,** 106-113.

Easley, D. & Kleinberg, J. 2010. *Networks, crowds, and markets: Reasoning about a highly connected world*, Cambridge University Press.

Gardener, L. M., Bar-Gera, H. & Boyles, S. D. 2013. An Evaluation Framework for High-Occupancy/Toll (HOT) Lanes.In *92nd Annual Meeting of Transportation Research Board Washington, D.C.*

Gasser, T. M. & Westhoff, D. 2012. BASt-study: Definitions of automation and legal issues in Germany.In *Proceedings of the 2012 Road Vehicle Automation Workshop*.

Greenshields, B. D. 1935. A Study of Traffic Capacity. *Highway Research Board Proceedings,* 14**,** 448-447.

Hampton Roads Planning District Commission. 2016. *Census Data* [Online]. Available: http://www.hrpdcva.gov/uploads/docs/Economic%20Characteristics.pdf [Accessed November 2016].

Harsanyi, J. C. 2004. Games with incomplete information played by "Bayesian" players, i–iii: part i. the basic model&. *Management science,* 50**,** 1804-1817.

Iftode, L., Smaldone, S., Gerla, M. & Misener, J. 2008. Active highways (position paper).In *2008 IEEE 19th International Symposium on Personal, Indoor and Mobile Radio Communications*. https://doi.org/10.1109/PIMRC.2008.4699958.

Isukapati, I. K. & List, G. F. 2015. Agent based framework for modeling operations at isolated signalized intersections.In *Intelligent Transportation Systems (ITSC), 2015 IEEE 18th International Conference on*.

Iwanowski, S., Spering, W. & Coughlin, W. J. 2003. Road traffic coordination by electronic trading. *Transportation Research Part C: Emerging Technologies,* 11**,** 405-422. https://doi.org/10.1016/S0968-090X(03)00033-0.

Jou, R.-C., Chiou, Y.-C., Chen, K.-H. & Tan, H.-I. 2012. Freeway drivers' willingness-to-pay for a distance-based toll rate. *Transportation Research Part A: Policy and Practice,* 46**,** 549-559. https://doi.org/10.1016/j.tra.2011.11.012.

Kazimi, C. 1999. *Willingness-to-pay to reduce commute time and its variance: evidence from the San Diego I-15 congestion pricing project,* Institute of Transportation Studies, University of California.

Klein, I. & Ben-Elia, E. 2016. Emergence of cooperation in congested road networks using ICT and future and emerging technologies: A game-based review. *Transportation Research Part C: Emerging Technologies,* 72**,** 10-28. https://doi.org/10.1016/j.trc.2016.09.005.

Klemperer, P. 1999. Auction theory: A guide to the literature. *Journal of economic surveys,* 13**,** 227-286. http://dx.doi.org/10.1111/1467-6419.00083.

Krishna, V. 2009. *Auction theory,* Burlington, MA, Academic press.

Li, J. 2001. Explaining high-occupancy-toll lane use. *Transportation Research Part D: Transport and Environment,* 6**,** 61-74. https://doi.org/10.1016/S1361-9209(00)00013-4.

Li, Z. & Kuo, C. C. 2013. Design of discrete Dutch auctions with an uncertain number of bidders. *Annals of Operations Research,* 211**,** 255-272. https://doi.org/10.1007/s10479-013-1331-6.

Malvey, P. F., Archibald, C. M. & Flynn, S. T. 1995. Uniform-price auctions: evaluation of the treasury experience. *Office of Market Finance, US Treasury*. http://www.kellogg.northwestern.edu/faculty/weber/DECS-452/Treasury_Report.pdf.

Markose, S., Alentorn, A., Koesrindartoto, D., Allen, P., Blythe, P. & Grosso, S. 2007. A smart market for passenger road transport (SMPRT) congestion: An application of computational mechanism design. *Journal of Economic Dynamics and Control,* 31**,** 2001-2032. http://dx.doi.org/10.1016/j.jedc.2007.01.005.

Mcafee, R. P. & Mcmillan, J. 1987. Auctions and bidding. *Journal of economic literature,* 25**,** 699-738.

Menezes, F. M. & Monteiro, P. K. 2005. *An introduction to auction theory*, OUP Oxford.

Michalaka, D., Lou, Y. & Yin, Y. 2011. Proactive and robust dynamic pricing strategies for High Occupancy/Toll (HOT) Lanes.In *90th Annual Meeting of the Transportation Research Board, Washington, DC*.

Milgrom, P. R. & Weber, R. J. 1982. A Theory of Auctions and Competitive Bidding. *Econometrica,* 50**,** 1089-1122. 10.2307/1911865.

Mishra, D. & Garg, R. 2006. Descending price multi-item auctions. *Journal of Mathematical Economics,* 42**,** 161-179. http://dx.doi.org/10.1016/j.jmateco.2005.12.003.

Mishra, D. & Parkes, D. C. 2009. Multi-item Vickrey–Dutch auctions. *Games and Economic Behavior,* 66**,** 326-347. http://dx.doi.org/10.1016/j.geb.2008.04.007.

Mowday, M. 2006. Equity and High-Occupancy Toll Lanes: Literature Review and Minnesotans' Perceptions About I-394 High-Occupancy Toll Lanes.In *Transportation Research Board 85th Annual Meeting* (No.06-1502).

Myerson, R. B. 1981. Optimal auction design. *Mathematics of operations research,* 6**,** 58-73.

National Highway Traffic Safety Administration, 2013. Preliminary statement of policy concerning automated vehicles. *Washington, DC*, pp.1-14. Available: https://www.nhtsa.gov/staticfiles/rulemaking/pdf/Automated_Vehicles_Policy.pdf.

Odeck, J. & Bråthen, S. 1997. On public attitudes toward implementation of toll roads—the case of Oslo toll ring. *Transport policy,* 4**,** 73-83. https://doi.org/10.1016/S0967-070X(97)00008-5.

Odeck, J. & Kjerkreit, A. 2010. Evidence on users' attitudes towards road user charges—A cross-sectional survey of six Norwegian toll schemes. *Transport Policy,* 17**,** 349-358. http://dx.doi.org/10.1016/j.tranpol.2010.04.001.

Olarte, R. & Haghani, A. 2017. Introducing and testing a game-theoretic model for a lottery-based metering system in Minneapolis, United States. *Transport Policy*. https://doi.org/10.1016/j.tranpol.2017.03.007.

Ozbay, K., Yanmaz-Tuzel, O. & Holguín-Veras, J. 2006. Theoretical Derivation of Value of Travel Time and Demand ElasticityL: Evidence from New Jersey Turnpike Toll Road. *Transportation Research Record: Journal of the Transportation Research Board***,** 248-256. https://doi.org/10.3141/1985-27.

Pigou, A. 1920. The economics of welfare.

Podgorski, K. V. & Kockelman, K. M. 2006. Public perceptions of toll roads: A survey of the Texas perspective. *Transportation Research Part A: Policy and Practice,* 40**,** 888-902. http://dx.doi.org/10.1016/j.tra.2006.03.002.

Poole, R. W. 2014. Modernizing the U.S. Interstate Highway System via Toll Finance.In *93rd Transportation Research Board Annual Meeting Washington, D.C.*

Raphael, J., Maskell, S. & Sklar, E. 2015. From goods to traffic: first steps toward an auction-based traffic signal controller.In *International Conference on Practical Applications of Agents and Multi-Agent Systems*. https://doi.org/10.1007/978-3-319-18944-4_16.

Ravi, N., Smaldone, S., Iftode, L. & Gerla, M. 2007. Lane reservation for highways (position paper).In *2007 IEEE Intelligent Transportation Systems Conference*. https://doi.org/10.1109/ITSC.2007.4357746.

Reichert, A. O., 1968. MODELS FOR COMPETITIVE BIDDING UNDER UNCERTAINTY.

Riley, J. G. & Samuelson, W. F. 1981. Optimal auctions. *The American Economic Review,* 71**,** 381-392.

Rstudio, T. 2014. RStudio: integrated development for R. *RStudio, Inc., Boston, MA.* http://www.RStudio.com/.

Safirova, E., Gillingham, K., Harrington, W. & Nelson, P. 2003. Are hot lanes a hot deal? the potential consequences of converting hov to hot lanes in northern virginia. *RFF Issue Brief***,** 03-03.

Schade, J. & Schlag, B. 2003. Acceptability of urban transport pricing strategies. *Transportation Research Part F: Traffic Psychology and Behaviour,* 6**,** 45-61. http://dx.doi.org/10.1016/S1369-8478(02)00046-3.

Schepperle, H. & Böhm, K. 2008. Auction-based traffic management: Towards effective concurrent utilization of road intersections.In *E-Commerce Technology and the Fifth IEEE Conference on Enterprise Computing, E-Commerce and E-Services, 2008 10th IEEE Conference on*.

Schoettle, B. & Sivak, M., 2014a. A survey of public opinion about autonomous and self-driving vehicles in the US, the UK, and Australia. Available: http://hdl.handle.net/2027.42/108384.

Schoettle, B. & Sivak, M. 2014b. A Survey of Public Opinion about Connected Vehicles in the US, the UK, and Australia.In *2014 International Conference on Connected Vehicles and Expo (ICCVE)*. https://doi.org/10.1109/ICCVE.2014.7297637.

Sumalee, A. 2001. Analysing the design criteria of charging cordons. http://eprints.whiterose.ac.uk/2066/1/ITS41_WP560_uploadable.pdf.

Teodorović, D., Triantis, K., Edara, P., Zhao, Y. & Mladenović, S. 2008. Auction-based congestion pricing. *Transportation Planning and Technology,* 31**,** 399-416. http://dx.doi.org/10.1080/03081060802335042.

Train, K. E. 2009. *Discrete choice methods with simulation*, Cambridge university press.

Ungemah, D. & Collier, T. 2007. I'll Tell You What I Think!: A National Review of How the Public Perceives Pricing. *Transportation Research Record: Journal of the Transportation Research Board*. https://doi.org/10.3141/1996-09.

Vasirani, M. & Ossowski, S. 2011. A computational market for distributed control of urban road traffic systems. *IEEE Transactions on Intelligent Transportation Systems,* 12**,** 313-321. https://doi.org/10.1109/TITS.2011.2104956.

Vasirani, M. & Ossowski, S. 2012. A market-inspired approach for intersection management in urban road traffic networks. *Journal of Artificial Intelligence Research,* 43**,** 621-659. http://dx.doi.org/10.1613/jair.3560.

Vickrey, W. 1961. Counterspeculation, auctions, and competitive sealed tenders. *The Journal of finance,* 16**,** 8-37.

Vickrey, W. 1962. Auctions and bidding games. *Recent advances in game theory,* 29**,** 15-27.

Vickrey, W. S. 1969. Congestion Theory and Transport Investment. *The American Economic Review,* 59**,** 251-260. http://www.jstor.org/stable/1823678.

Vijay, K. 2002. Auction theory. Academic press.

Wie, B.-W. 2007. Dynamic Stackelberg equilibrium congestion pricing. *Transportation Research Part C: Emerging Technologies,* 15**,** 154-174.

Yang, F. 2008. Day-to-day dynamic optimal tolls with elastic demand.In *Transportation Research Board 87th Annual Meeting* (No.08-0305).

Zhang, G., Ma, X. & Wang, Y. 2014. Self-Adaptive Tolling Strategy for Enhanced High-Occupancy Toll Lane Operations. *IEEE Transactions on Intelligent Transportation Systems,* 15**,** 306-317.

Zhang, G., Wang, Y., Wei, H. & Yi, P. 2008. A feedback-based dynamic tolling algorithm for high-occupancy toll lane operations. *Transportation Research Record: Journal of the Transportation Research Board,* 2065**,** 54-63. https://doi.org/10.3141/2065-08.

Zhou, H. & Saigal, R. 2014. A Combinatorial Auction to Allocate Traffic.In *Transportation Research Board 93rd Annual Meeting Washington, D.C.*

Zmud, J. P., Peterson, S. & Douma, F. 2007. Preliminary Before and After Results of I-394 HOT Lane Panel Survey.In *Transportation Research Board 86th Annual Meeting* (No.07-0048).

6.0 APPENDICES

A-1 APPENDIX
ONLINE SURVEY QUESTIONNAIRE

Understanding Public Experience and Perception of Newly Designed Tolling Mechanisms

Introduction: The purpose of this study is to evaluate the public's understanding of new alternatives for toll collection on hypothetical highways, and how drivers would react to these new tolling methods.

Researchers:

- Mecit Cetin, Ph.D., Director of the Transportation Research Institute, Old Dominion University
- Lei Zhang, PhD, Herbert Rabin Distinguished Professor, Department of Civil and Environmental Engineering, University of Maryland
- Andrew J. Collins, Ph.D., Research Faculty, Virginia Modeling and Simulation Center, Old Dominion University
- R. Michael Robinson, Ph.D., Director of the Center for Innovative Transportation Solutions, Old Dominion University
- Erika Frydenlund, Ph.D., Senior Project Scientist, Virginia Modeling and Simulation Center, Old Dominion University
- Gulsevi Basar, Ph.D. Student, Department of Civil & Environmental Engineering, Old Dominion University

Description: This study will use survey responses to evaluate the public's understanding of new alternatives for toll collection on hypothetical highways, and how well drivers comprehend new tolling methods to determine toll prices. If you agree to participate, you will support a study that looks at how well real-world drivers can understand futuristic toll pricing strategies. The survey will take approximately 20-30 minutes to complete. It will require you to select some answers and type in others. Approximately 100 people will take part in this study. There is no financial cost to you, but also no financial compensation for your participation.
Confidentiality: The researchers will take all possible steps to keep the information you supply private. The results of this study may be used in reports, presentations, and publications; but the researcher will not identify you. These results may include quotes from survey answers, but no private or personally identifiable information will be associated with these quotes in order to protect the identity, safety, and privacy of you and other participants.
Withdrawal Privilege: It is OK for you to say NO. Even if you say YES now, you are free to say NO later, and walk away or withdraw from the study at any time. If you have questions or concerns about the study, please contact: mcetin@odu.edu

By clicking "Yes, I agree to participate" below, you are verifying that you have read the explanation of the study and that you agree to participate strictly voluntarily. You may quit the survey at any time if you wish to not continue. *

○ Yes, I agree to participate in this study.

○ No, I do not agree to participate in this study.

Next

0%

SECTION 1

The following section consists of several different scenarios depicted in visuals for two new tolling mechanisms. The section consists of two parts called **"Tolling Method 1"** and **"Tolling Method 2".**

In both scenarios, you are assumed to travel through a corridor for an appointment and informed about the travel times on two different routes. These scenarios take place in a futuristic setting. For these scenarios, assume that you have access to a technology that allows you to communicate your toll price preferences safely **without interrupting your ability to drive.**

All the information given for a scenario will be depicted in the visual attached to the question. Please consider that **given road capacity is for easy demonstration purposes**, **and does not reflect the overall capacity of a road in real life.**

You are required to answer each question **within the allotted time (e.g., 30 seconds, 45 seconds, and 60 seconds).**

The section is expected to take 10-20 minutes.

Next

4%

Tolling Method 1

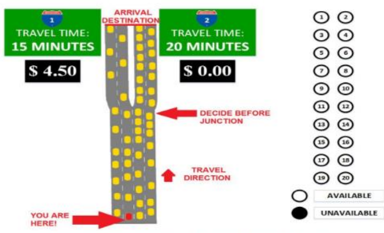
In this section, you will be presented different traffic scenarios under "**Tolling Method 1**". In these scenarios, you will be asked to choose one of two routes: a toll route and a general route. Travel times on these routes are different as indicated on the visuals and the trip is your regular **daily commute from work or school to home or home to work or school.**

You should imagine you are traveling in the direction shown by the arrow in the visual. You will have multiple but **limited** chances to access the toll road, and you will be presented **different prices at each step**. Also, you should answer each question **within allotted time** presented on the count-down clock (at the bottom or top of the browser window depending whether you are using a PC or tablet).

Next

7%

Tolling Method 1



Please answer the question based on the scenario depicted in visual above.

Only **20 cars** will be allowed to take Route 1. *

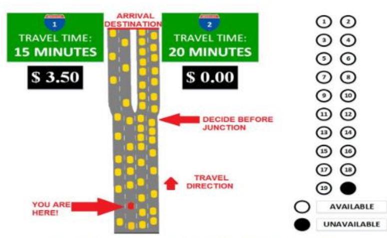
- ◯ I will use **toll road**, **pay $4.50, and travel 15 minutes**
- ◯ I will use **toll-free road and travel 20 minutes**

Next

11%

Time Left on this Section: 0:00:55

Tolling Method 1



Please answer the question based on the scenario depicted in this visual above.

Only **19 cars** will be allowed to take Route 1. *

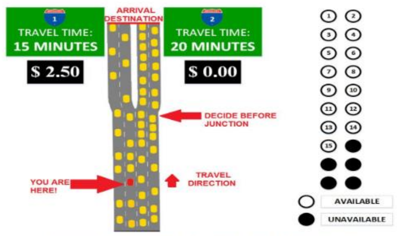
- ◯ I will use **toll road, pay $3.50 and travel 15 minutes**
- ◯ I will use **toll-free road and travel 20 minutes**

Next

13%

Time Left on this Section: 0:00:57

Tolling Method 1



Please answer the question based on the scenario depicted in this visual above.

Only **15 cars** will be allowed to take Route 1. *

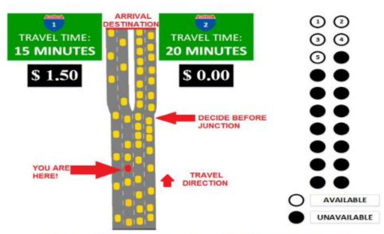
- ◯ I will use **toll road, pay $2.50 and travel 15 minutes**
- ◯ I will use **toll-free road and travel 20 minutes**

Next

15%

Time Left on this Section: 0:00:40

Tolling Method 1



Please answer the question based on the scenario depicted in this visual above.

Only **5 cars** will be allowed to take Route 1. *

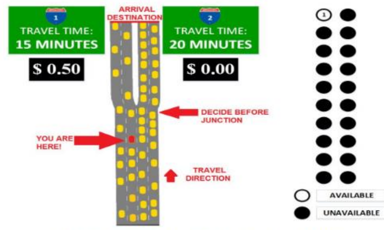
- ◯ I will use **toll road, pay $1.50 and travel 15 minutes**
- ◯ I will use **toll-free road and travel 20 minutes**

Next

17%

Time Left on this Section: 0:00:56

Tolling Method 1



Please answer question based on the scenario depicted in this visual above.

Only **1 car** will be allowed to take Route 1.
*

- ◯ I will use **toll road, pay $0.50 and travel 15 minutes**
- ◯ I will use **toll-free road and travel 20 minutes**

Next

20%

Time Left on this Section: 0:00:54

We are sorry!

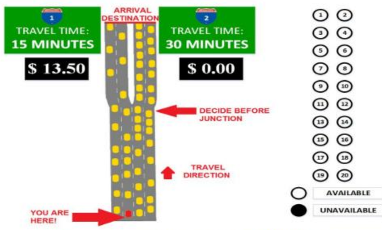
Available slots on the toll road are sold out! It is predicted that you will travel for 20 minutes on toll-free road.

Now please continue with the next question.

Next

22%

Tolling Method 1



Please answer the question based on the scenario depicted in this visual above.

Only **20 cars** will be allowed to take Route 1. *

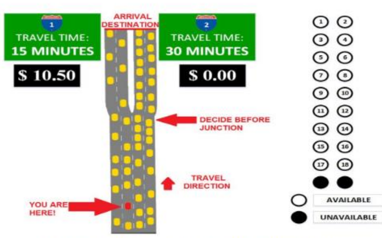
- ◯ I will use **toll road, pay $13.50 and travel 15 minutes**
- ◯ I will use **toll-free road and travel 30 minutes**

Next

24%

Time Left on this Section: 0:00:41

Tolling Method 1



Please answer the question based on the scenario depicted in this visual above.

Only **18 cars** will be allowed to take Route 1. *

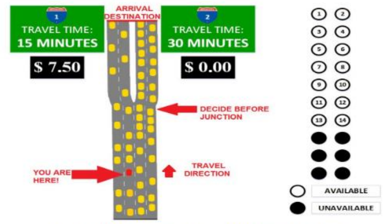
- ◯ I will use **toll road, pay $10.50 and travel 15 minutes**
- ◯ I will use **toll-free road and travel 30 minutes**

Next

26%

Time Left on this Section: 0:00:42

Tolling Method 1



Please answer the question based on the scenario depicted in this visual above.

Only **14 cars** will be allowed to take Route 1.
*

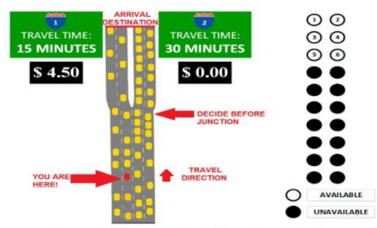
- ◯ I will use **toll road, pay $7.50, and travel 15 minutes**
- ◯ I will use **toll-free road and travel 30 minutes**

Next

28%

Time Left on this Section: 0:00:42

Tolling Method 1



Please answer the question based on the scenario depicted in this visual above.

Only **6 cars** will be allowed to take Route 1.
*

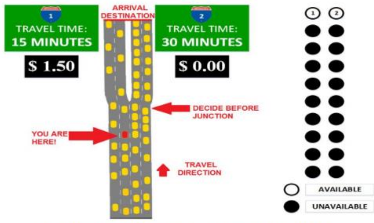
- ◯ I will use **toll road, pay $ 4.50 and travel 15 minutes**
- ◯ I will use **toll-free road and travel 30 minutes**

Next

30%

Time Left on this Section: 0:00:42

Tolling Method 1



Please answer the question based on the scenario depicted in this visual above.

Only **2 cars** will be allowed to take Route 1. *

- ◯ I will use **toll road, pay $1.50 and travel 15 minutes**
- ◯ I will use **toll-free road and travel 30 minutes**

Next

33%

Time Left on this Section: 0:00:42

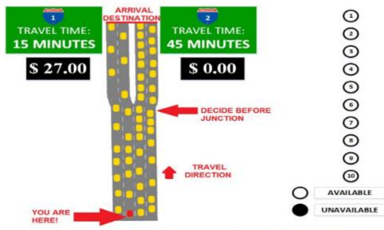
You accepted to pay the toll and can take the toll road.

Now please continue with the next question.

Next

35%

Tolling Method 1



Please answer the question based on the scenario depicted in this visual above.

Only **10 cars** will be allowed to take Route 1.
*

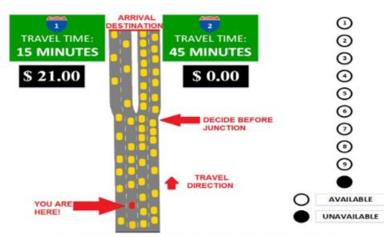
- I will use **toll road , pay $27.00 and travel 15 minutes**
- I will use **toll-free road and travel 45 minutes**

Next

37%

Time Left on this Section: 0:00:27

Tolling Method 1



Please answer the question based on the scenario depicted in this visual above.

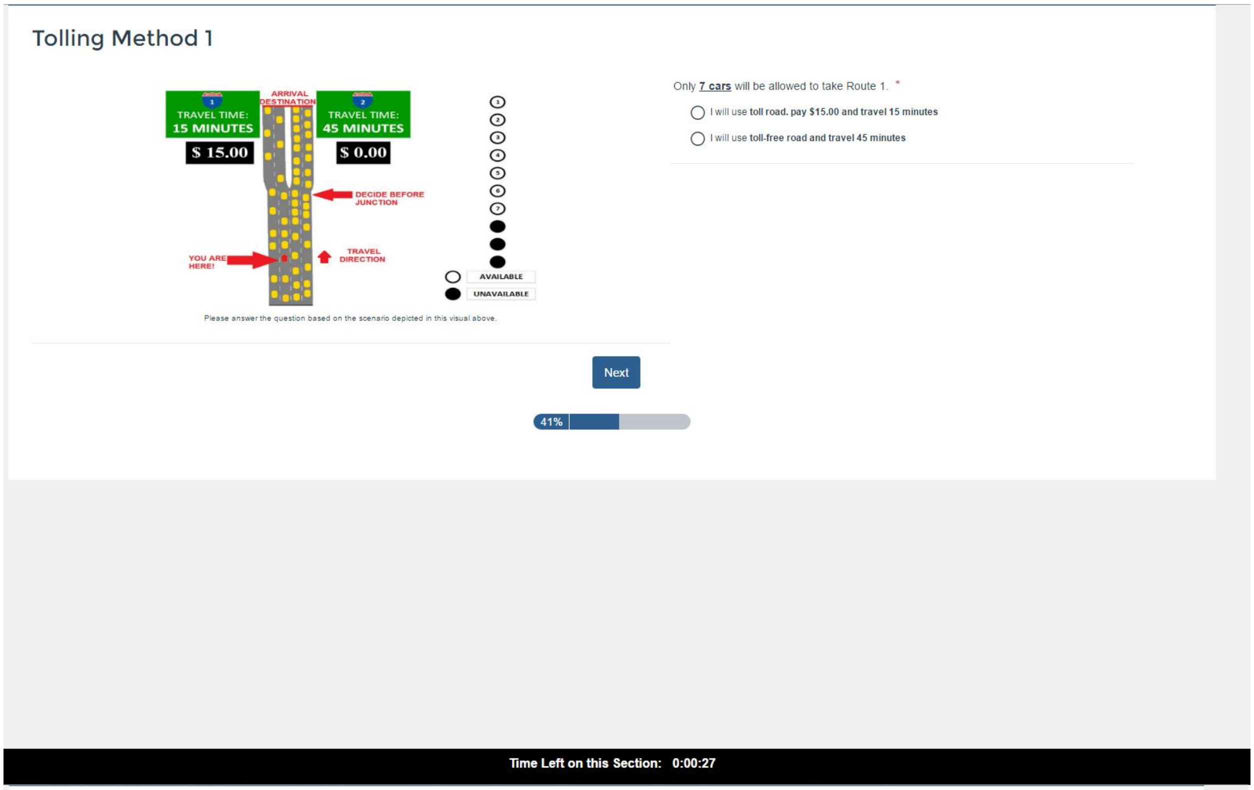
Only **9 cars** will be allowed to take Route 1.
*

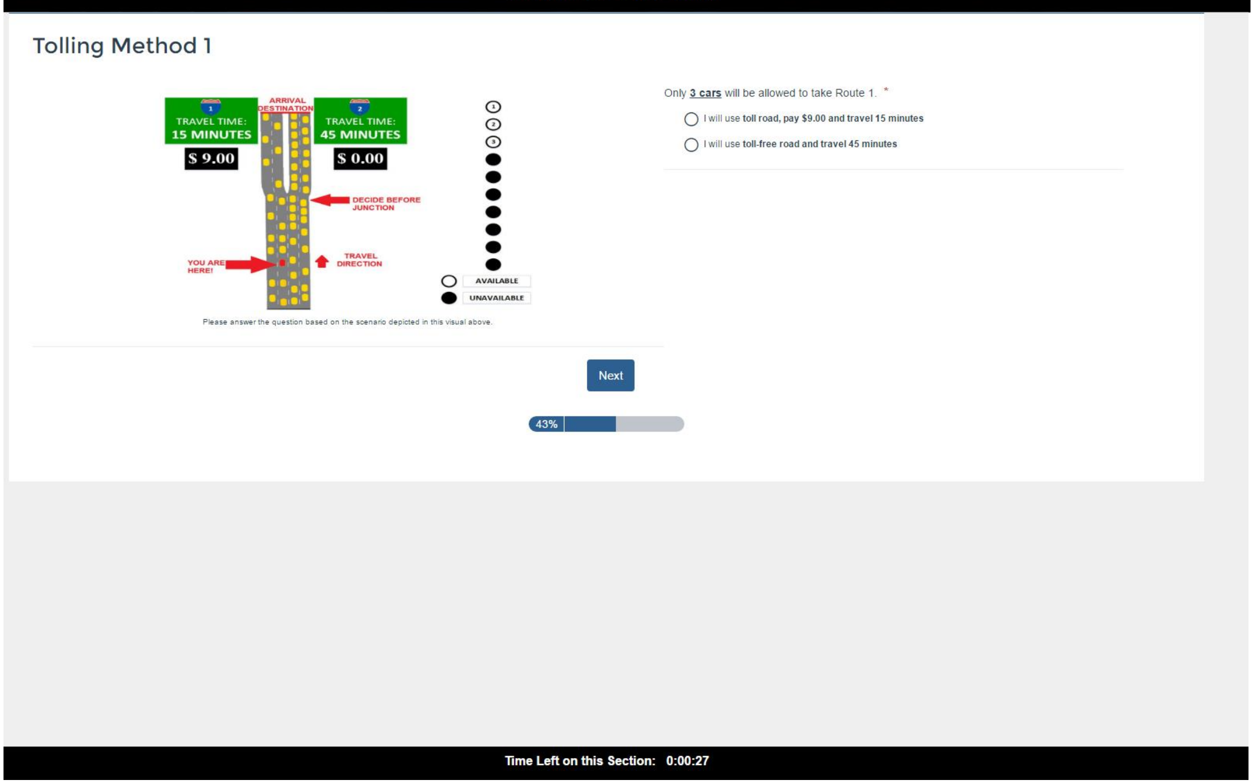
- I will use **toll road, pay $ 21.00 and travel 15 minutes**
- I will use **toll-free road and travel 45 minutes**

Next

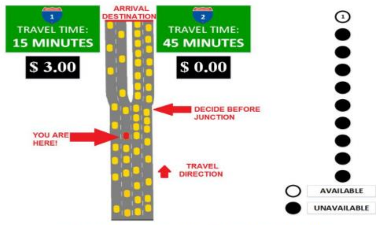
39%

Time Left on this Section: 0:00:26


Tolling Method 1
TRAVEL TIME: 15 MINUTES
$ 15.00
ARRIVAL DESTINATION
TRAVEL TIME: 45 MINUTES
$ 0.00
DECIDE BEFORE JUNCTION
YOU ARE HERE!
TRAVEL DIRECTION
AVAILABLE
UNAVAILABLE
Please answer the question based on the scenario depicted in this visual above.
Only 7 cars will be allowed to take Route 1. *
I will use toll road, pay $15.00 and travel 15 minutes
I will use toll-free road and travel 45 minutes
Next
41%
Time Left on this Section: 0:00:27


Tolling Method 1
TRAVEL TIME: 15 MINUTES
$ 9.00
ARRIVAL DESTINATION
TRAVEL TIME: 45 MINUTES
$ 0.00
DECIDE BEFORE JUNCTION
YOU ARE HERE!
TRAVEL DIRECTION
AVAILABLE
UNAVAILABLE
Please answer the question based on the scenario depicted in this visual above.
Only 3 cars will be allowed to take Route 1. *
I will use toll road, pay $9.00 and travel 15 minutes
I will use toll-free road and travel 45 minutes
Next
43%
Time Left on this Section: 0:00:27

Tolling Method 1



Please answer the question based on the scenario depicted in this visual above.

Only **1 car** will be allowed to take Route 1.
*

- ◯ I will use **toll road, pay $3.00 and travel 15 minutes**
- ◯ I will use **toll-free road and travel 45 minutes**

Next

46%

Time Left on this Section: 0:00:27

Tolling Method 2

In this section, you will be presented different traffic scenarios under "**Tolling Method 2**". In these scenarios, you will be asked to choose one of two routes: a toll route and a general route. Travel times on these routes are different as indicated on the visuals and the trip is your regular **daily commute** from work or school to home or home to work or school.

Imagine you are traveling in the direction shown by the arrow in the visual. You will be asked **only once to give the price you are willing to pay** to take the toll route.

Next

50%

Tolling Method 2

Please answer the question based on the scenario depicted in this visual above.

Please enter how much you are willing to pay to enter the toll road (Route 1).
*

Next

28%

We are sorry! Your offer to enter toll route is not accepted!

To enter the toll route, minimum price is determined to be $1.00.Would you willing to pay **at least** $1 to enter the toll route? *

- ○ Yes
- ⦿ No

Next

57%

Tolling Method 2

Please answer the question based on the scenario depicted in this visual above.

Please enter how much you are willing to pay to enter the toll road (Route 1). *

2.5

Next

59%

Your toll price offer is accepted and you can take the toll road.

Now please continue with the next question.

Next

61%

Tolling Method 2

Please answer the question based on the scenario depicted in this visual above.

Please enter how much you are willing to pay to enter the toll road. *

3.5

Next

63%

SECTION - 2

This section consists of questions to determine your understanding and opinion of the previous toll scenarios. It is expected to take 5 minutes.

Next

67%

Overall, **how well** did you feel you understood the way toll prices were determined in **Tolling Method 1**? *

Extremely	Very	Moderately	Slightly	Not at all
○	○	○	◉	○

Please use the comment box below to explain what caused confusion.

Next

70%

Overall, **how well** did you feel you understood the way toll prices were determined in **Tolling Method 2?** *

Extremely	Very	Moderately	Slightly	Not at all
○	○	○	◉	○

Please use the comment box below to explain what caused confusion.

Next

72%

Are you familiar how tolls are currently set in your area? *

- ◉ Yes
- ○ No

Would you prefer any of the new methods over the current one? *

- ○ Yes, Tolling Method 1
- ○ Yes, Tolling Method 2
- ○ Yes, any of the methods
- ○ No

Next

74%

Would you change the prices you were willing to pay if you had to pick up a dependent on time or need to go to the hospital emergency room? *

- Yes
- No

Do you think these tolling systems are age-friendly, particularly for senior drivers *

- Yes
- No

Please share any additional thoughts you have been on the tolling scenarios in this survey including fairness, potential benefits or harms, and feelings about convenience or confusion.

Next

76%

SECTION 3

This section consists of multiple choice questions regarding your demographic profile.

The section will take about 5 minutes. Please answer each question as accurately as possible. You are free to decline to answer a question at any time for any reason.

Next

78%

DEMOGRAPHICS

Please select your residential location. *

-- Please Select --

What is your gender? *

- Female
- Male
- Prefer not to answer

Select the category that includes your age. *

- 16 - 24
- 25 - 40
- 41 - 65
- 65+
- Prefer not to answer

Next

80%

DEMOGRAPHICS

What is the highest level of school you have completed or the degree you have received? *

- Less than high school
- High school or GED equivalent
- Associate degree or some college
- Bachelor degree
- Graduate degree
- Prefer not to answer

Are you employed? *

- Yes, I work full time
- Yes, I work part time
- No, unemployed
- Other ____ *
- Prefer not to answer

Next

83%

DEMOGRAPHICS

Which one best describes your household income? *

- $ 35,000 or less
- $ 35,001 - $ 50,000
- $ 50,001 - $ 100,000
- $ 100,001 or more
- Prefer not to answer

How many people live in your household **including** you? *

For commuting to work, school etc., do you typically drive? *

- Yes
- No

Submit

98%

Thank You!

Thank you for taking our survey. Your response is very valuable to us.

100%