AUCTION-BASED TOLLING SYSTEMS IN A CONNECTED AND AUTOMATED VEHICLES ENVIRONMENT: PUBLIC OPINION AND IMPLICATIONS FOR TOLL REVENUE AND CAPACITY UTILIZATION

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Abstract

Autonomous and connected vehicles are expected to enable new tolling mechanisms, such as auction-based tolls, for allocating the limited roadway capacity. This research examines the public perception of futuristic auction-based tolling systems, with a particular focus on the public acceptance of such systems over current tolling practices on highways (e.g., dynamic and fixed tolling methodologies). In particular, through a stated-preference survey, responses from 159 road-users residing in Virginia are elicited to understand route choice behavior under a descending price auction implemented on a hypothetical two-route network. Analysis of the survey data shows that there is no outright rejection of the presented auction-based tolling among those who are familiar with the current tolling methods. While males strongly support the new method, no clear pattern emerges among other demographic variables such as income and education level, and age. While high income respondents and regular commuters are more likely to pay higher tolls, no statistical significance between different genders, age groups, household sizes, and education levels is found. Based on the modeling results and the hypothetical road network, it is found that descending price tolling method yields higher average toll rates, and generates at least 70% more revenue when travel time saving is 30 minutes, and improves capacity utilization of the toll road significantly compared to fixed tolls.

Keywords

Auction-based tolling, connected vehicles, autonomous vehicles, online survey, public attitudes, choice models

Highlights

- We propose a novel tolling system based on descending price auction.
- Online survey is conducted to assess public attitudes towards the proposed method.
- New method generates more revenue compared to fixed tolling.
- New method provides better toll capacity utilization compared to fixed tolling.
- New tolling method does not negatively affect low income groups substantially.

1. Introduction

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 in Pigou's seminal paper (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 (Jou, Chiou, Chen, & Tan, 2012; Yang, 2008; Zhang, Wang, Wei, & Yi, 2008). 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, Ghosh, Golob, Kazimi, & Van Amelsfort, 2003; Zmud, Peterson, & Douma, 2007).

New vehicle technologies such as connected and fully automated vehicles (CAVs) will be entering the roadways sooner than expected as transportation-related technologies rapidly evolve. These vehicles with full automation are expected to perform all critical driving activities and safety decisions while monitoring the traffic conditions (Gasser & Westhoff, 2012; NHTSA, 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 central control parameters such as travel distance, and travel demand, but also on the drivers' interests and strategies. By giving drivers a degree of autonomy over tolls to be paid, market competition shall be created. It is practically proven that market competition adapts rapidly to the unexpected changes in economy better than centrally controlled markets. Similar to this approach, competition among drivers is necessary to respond changes in traffic conditions rapidly to alleviate the effects of traffic congestion. 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 guidance problem under congestion. Different auctioning techniques on the highways are later discussed and supported by several other researchers (Collins, Frydenlund, Robinson, & Cetin, 2015; Su & Park, 2015; Zhou & Saigal, 2014a).

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 (Schade & Schlag, 2003; Sumalee, 2001). To alleviate public opposition to congestion pricing, some researchers suggested alternative options, such as transit incentives and subsidies on alternative un-tolled roads (Adler & 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 & Bråthen, 1997; Odeck & Kjerkreit, 2010; Podgorski & Kockelman, 2006). Second body of research studies focus on public perception of connected and autonomous vehicles. Schoettle and Sivak 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, 2014b). 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 paper, an online stated preference survey is conducted 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). Full automation is considered to be 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 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 (Z. Li & 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). In this case, an earlier study showed that descending price auctions for multi-item auctions can continue until all items are sold and a price vector close to competitive prices can be achieved (Mishra & Garg, 2006; Mishra & 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 paper is organized as follows: the next section gives a brief discussion of public attitudes towards tolling and CAVs, 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. Literature review

CAVs are one of the most exciting technological advances soon to be adopted in our daily transport. Companies like Google, Audi, and General Motors have started testing their autonomous vehicle prototypes that they developed, while transportation agencies in several states such as California, Nevada, and Michigan have enacted legislation for CAVs to be tested on the roads (Schoettle & 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 & 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 & Sivak, 2014a, 2014b). With the coming adoption of AV and CV technologies, opportunities for alternative tolling schemes arise. However, as the following sections discuss, 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; J. Li, 2001; Ozbay, Yanmaz-Tuzel, & Holguín-Veras, 2006). This 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 are allowed to bid for spots on a tolled facility that provides less congestion and more reliable travel times. Auctions facilitate competitive bidding processes in a number of 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 for tolling enabled by V2I technologies have already been proposed by several scholars. Zhou and Saigal (2014b) used a combinatorial auctioning approach, specifically the computationally intensive Vickrey-Clarke-Groves (VCG) mechanism, to allocate traffic on toll roads in an interconnected traffic network. In this method, first, the price that maximizes revenue is determined, and then traffic is allocated on the road network. They proved that the proposed system maximizes social utility and guarantees truthful bidding. Collins et al. (2015) 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. Unlike Zhou and Saigal, and Collins et al., Markose et al. (2007) implemented a sealed-bid uniform price Dutch auction with cap-and-trade market approach 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.

While ascending price auctions are suitable for unique items and therefore, not considered in this study, their theoretical counter-part second price sealed-bid auctions are found to be more appropriate in static environments, even though the dominant strategy of truthful bidding is guaranteed (Collins et al., 2015; Klemperer, 1999; Zhou & Saigal, 2014b). Descending price auctions, on the other hand, are famous for their speed, and dynamicity for perishable goods which need to be sold quickly. 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 & 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 & Garg, 2006).

3. Proposed descending price 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, in order 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 (Iftode, Smaldone, Gerla, & Misener, 2008; Ravi, Smaldone, Iftode, & Gerla, 2007). 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, Archibald, & Flynn, 1995). This is also similar to 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 considered to be 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.

4. Data Source and methodology

This section discusses the design, development, and the administration of the online stated preference survey and the estimated discrete choice model structure and the simulation method adopted for the purpose of comparing fixed-tolling to descending price auction. The section also presents the summary of survey participants' demographics.

4.1. Survey design and development

An online survey was conducted using SurveyGizmo (https://www.surveygizmo.com/). The questionnaire 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 a number of driving scenarios within a certain case of descending price auction method as described in Section 3.

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.

4.1.1. Auction-based tolling scenarios

In the online survey, respondents were presented with three descending price auction cases, each including five bid levels in order 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, Nelson, Kelly, Gupta, & Cho, 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.

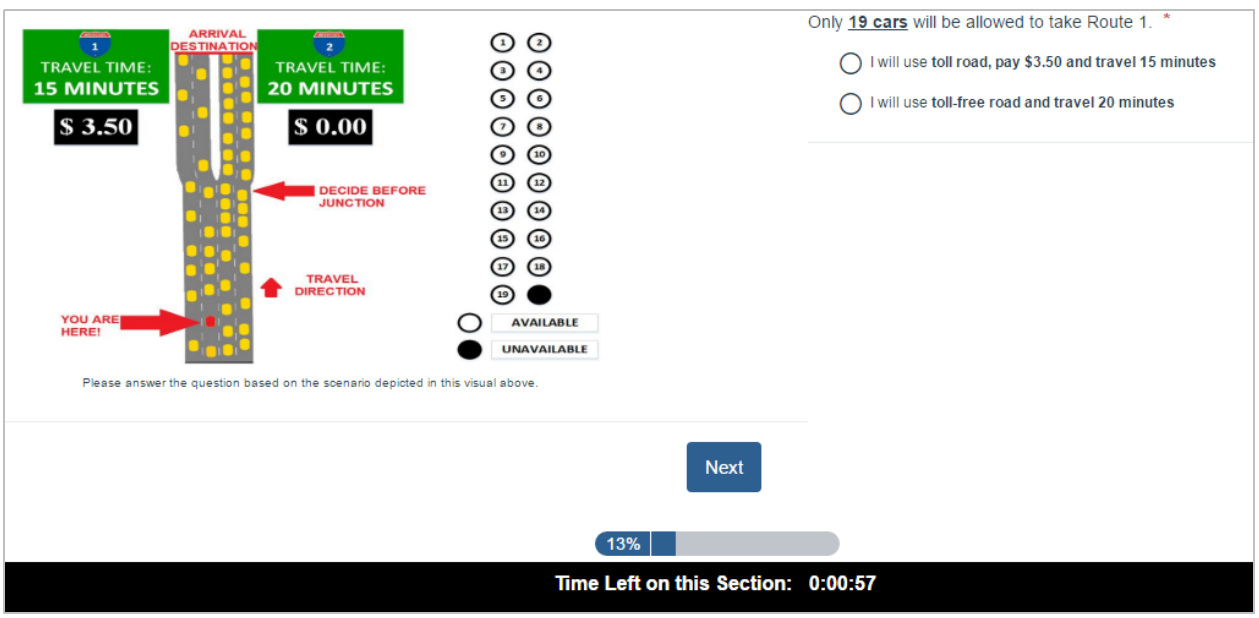

Figure 1 Sample visual depicting a descending price auction tolling choice question in the online survey

4.1.2. 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.

4.1.3. 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.

4.2. 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, 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.

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%

4.3. Discrete choice model structure 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 5.3, 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:

$$U_{iq} = \beta X_{iq} + \varepsilon_{iq} \quad (1)$$

where

i = index for route, $i = 1$, or 2, because there are two routes in the scenarios presented
q =index of individuals
X_{iq} =vector of explanatory variables specific to individual q and route i
β = parameters corresponding to the explanatory variables to be estimated
U_{iq} =the utility associated with route i for individual q
ε_{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:

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

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 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:

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

where

i = index for route, $i = 1$, or 2, because there are two routes in the scenarios presented
q = index of individuals
t = index for choice situation individual q is facing
X_{iq} = vector of explanatory variable specific to individual q and route i
β = parameters corresponding to the explanatory variables to be estimated
U_{iq} = the utility associated with route i for individual q
η_{iq} =random term dependent over individuals and underlying data and parameters
ε_{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.

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

In this study, mixing distributions among parameters are considered to be 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).

4.4. Simulation of route choice behavior

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

In order to compare the two tolling systems, a hypothetical network similar to 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 5.2. 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. In order 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 5.3.1). The implications of descending price auction on different income groups are demonstrated (see section 5.3.2). 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 5.3.3).

5. Results and discussion

5.1. 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 3.81, respondents with no familiarity rated their comprehension as 3.69. The analysis of opponents' comments gave important insights into shortcomings of proposed methods. Some opponents stated that they dislike to pay tolls in general, and they consider to look 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 & Bråthen, 1997; Ungemah & 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.

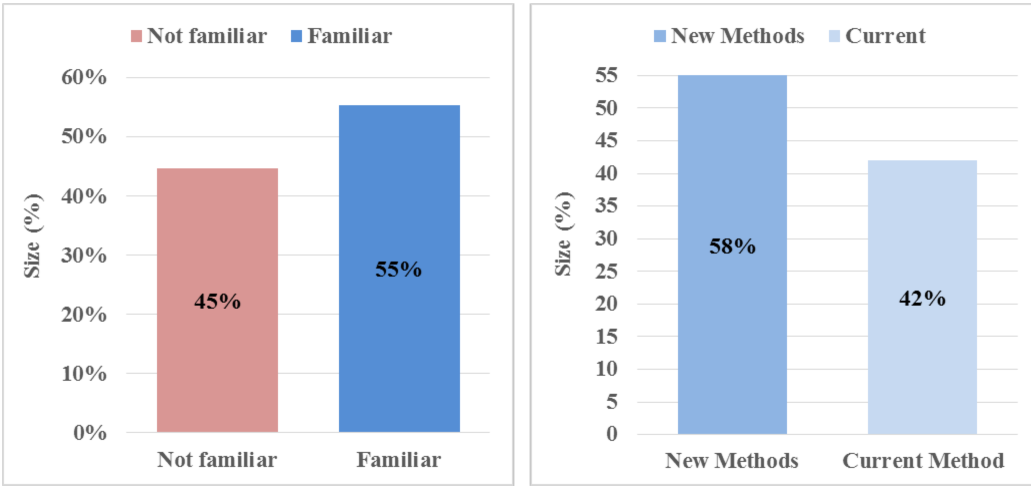

Figure 2 Indicated toll familiarity of the participants (left) and indicated preference for tolling method (right)

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. Similar to 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.

5.2. Model estimation results 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 since each bid level had a separate binary choice made by the respondents within each case. These choices at each bid level are "using toll-free lane" and "paying toll rate to save time". As it was shown in 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 considered to be an independent choice situation for the respondent. The respondent is expected to choose between two alternatives: toll route and toll-free route at each choice situation. Each choice situation the respondent faced with is treated as a separate observation in the model estimation procedure. Overall, across 3 cases, 2072 observations are obtained that are used in model estimation. The restructured data was weighted based on income levels of the Hampton Roads area population (HRPDC, 2016). The population size, and sample size of each income level along with used weights are shown in Table 3.

Table 3 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 4. Tested variables were considered to be 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 4 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 & 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 together 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 considered to be 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 the majority 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 were 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.

5.3. 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 (HRPDC, 2016). The desired capacity of the toll road is assumed to be 1,800 vehicles per hour, while maximum and minimum toll rates are set to \$0.90 and \$0.10 per minute time savings. 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 one random probability of accepting a toll offer. 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, two different sensitivity analysis 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. The implications of descending price auction tolling on different income groups are also investigated to understand how the system affects high and low income groups differently. The results are presented in Section 5.3.1 and Section 5.3.2, respectively. Second, the effect of the number of bid levels (the number of times the driver is asked a toll rate) is evaluated to understand how it affects the revenue collected.

5.3.1. 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 4.4.

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 in order 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 5.

Table 5 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	Maximum Toll	Minimum Toll	Toll Decrement
10	$ 2.50	$ 1.00	$ 1.00	$ 1.00	$ 9.00	$ 2.00
15	$ 3.00	$ 1.95	$ 1.95	$ 1.50	$ 13.50	$ 3.00
20	$ 4.00	$ 3.10	$ 3.10	$ 2.00	$ 18.00	$ 4.00
25	$ 5.00	$ 4.30	$ 4.30	$ 2.50	$ 22.50	$ 5.00
30	$ 6.00	$ 5.45	$ 5.45	$ 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 5. 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 5 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, 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 and average accepted toll rate in descending price auction tolling as shown in Table 5. It can be easily seen from the graph on the right in Figure 3 that descending price auction tolling is providing better and higher toll road capacity utilization than fixed tolling method does.

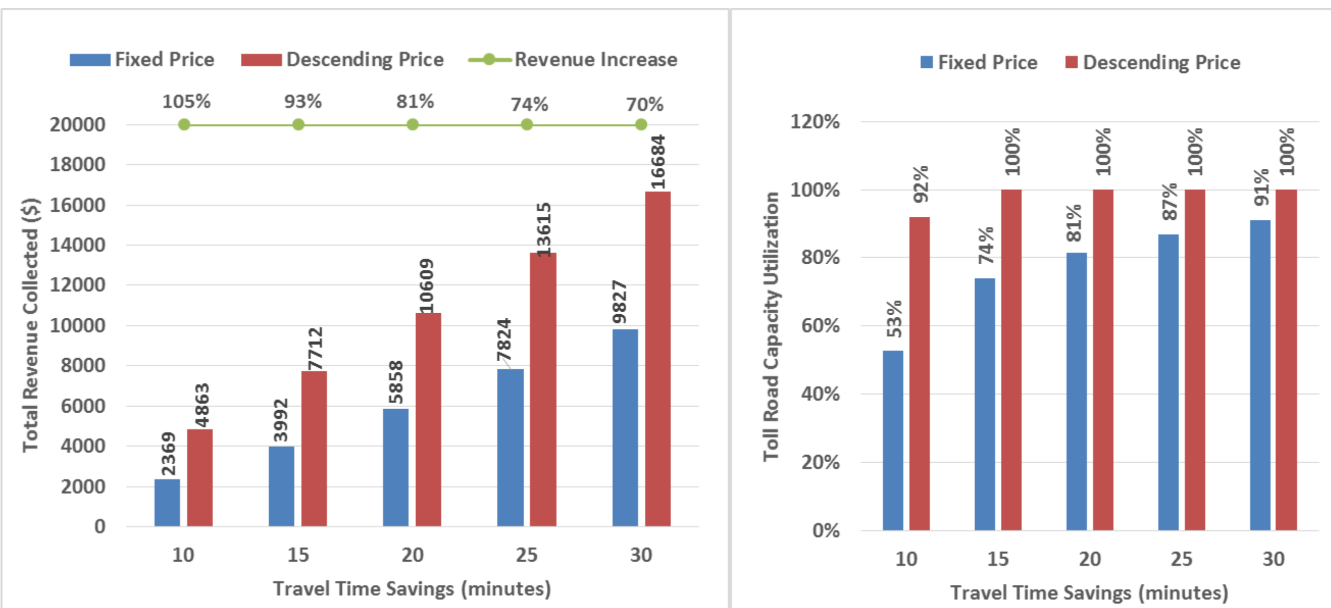

Figure 3 Comparison of revenue collected (left) under revenue maximizing fixed toll rate, and toll road capacity utilization (right) under utilization-maximizing fixed toll rate

5.3.2. 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 and low income groups, and what percentage of drivers who were willing to go on toll road are rejected due to capacity restriction. In Figure 4, 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 5. 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, 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.

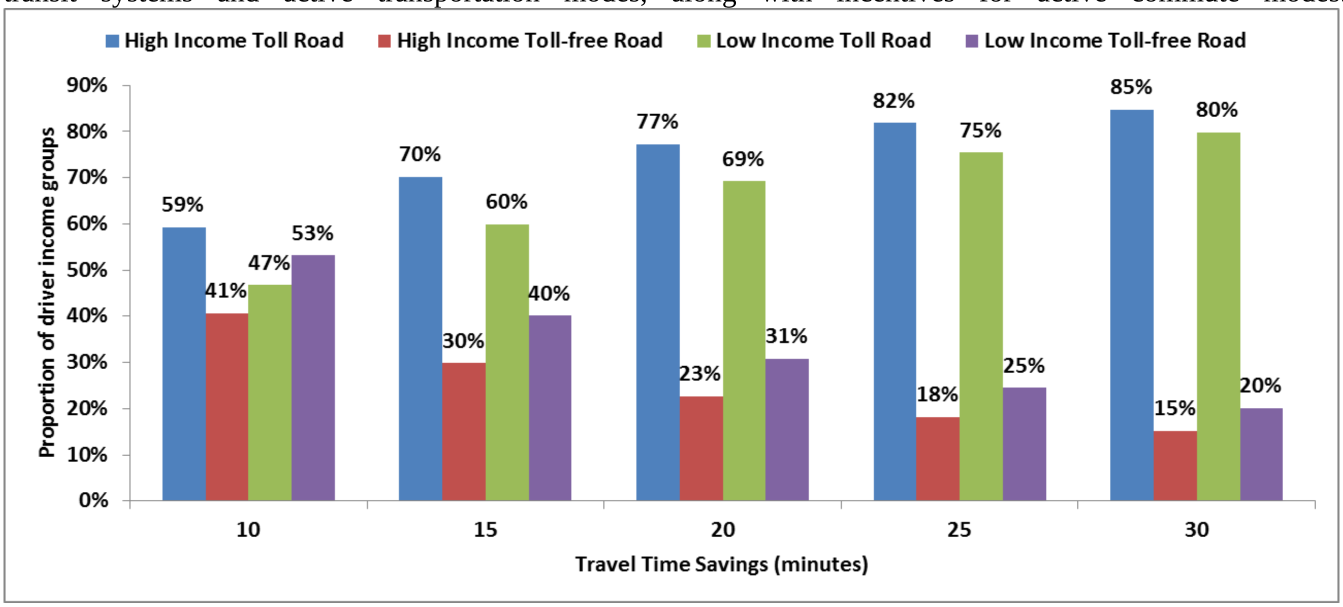

Figure 4 Ratio of drivers who accept or reject to use toll road across income groups

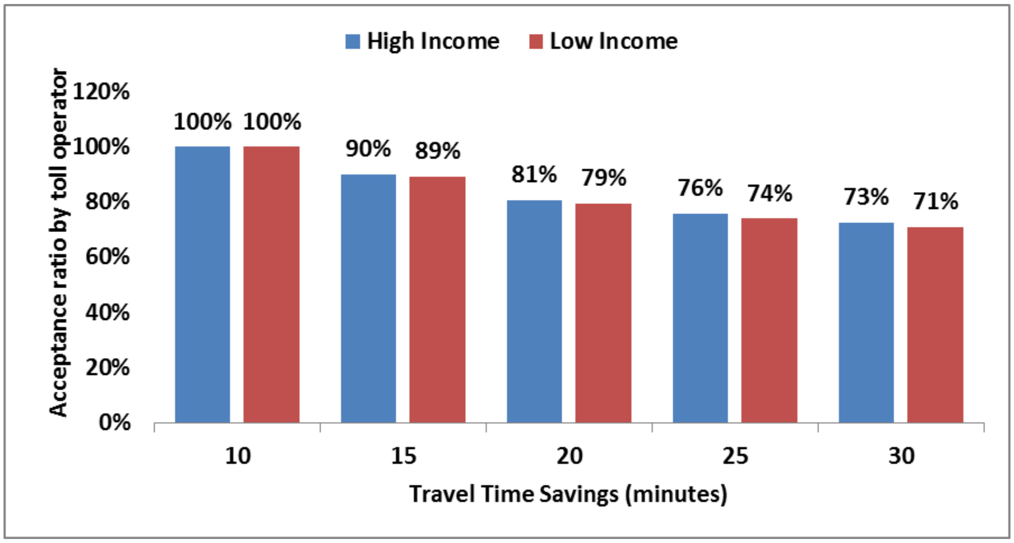

Figure 5 Toll operator's acceptance ratio of drivers across different income groups

5.3.3. 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 in order 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 6, 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.

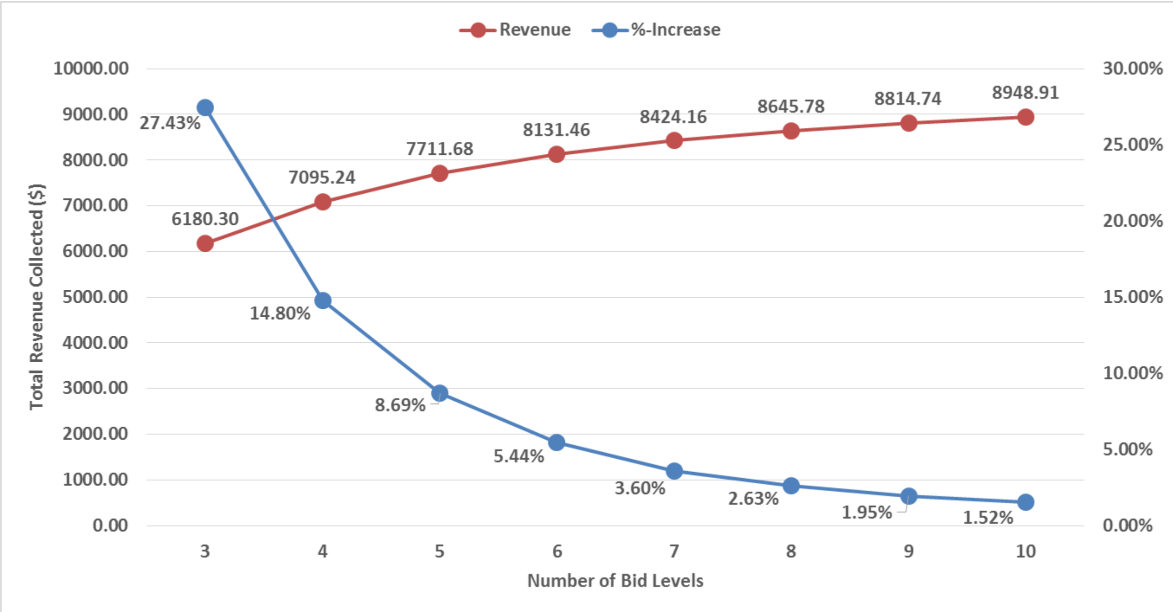

Figure 6 The effects of the number of bid levels on revenue collected at TTS 15 minutes

6. 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 model 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.

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. Survey penetration to low income respondents was an issue. These obstacles should be overcome in a future study.

6.1. Further Discussions and Future Research Direction

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 certain vehicle-toll operator unit, in which information regarding the trip purpose, toll budget etc. is adjusted by the driver, may also 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 was 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. In order to understand the effect of those, a lab experiment with driver-subjects may be conducted, or an online auction game for a number of driver-subjects can be conducted in order to eliminate the effect of pressure or excitement formed in a lab setting.

The choice models in this study did not take interdependency between consecutive decisions (bid levels) within a certain auction case scenario. We assumed each choice is an independent observation. The estimation of the choice model conditional to both previous and the next bid levels may be introduced in different ways, such as implementing a utility of not accepting a higher price and waiting for the next higher price. Also, it is another future direction to understand the risk-taking behavior of different drivers and how this behavior affects waiting behavior for the lower bidding price. For example, it is expected that risk-averse drivers will be accepting higher prices to guarantee a slot on toll road, while risk-neutral drivers will be waiting longer for lower toll rate offers.

The actual implementation of such system requires not only technological advancements and public acceptance, but also a robust simulation study to further explore the advantages and drawbacks of such design, and its effects on traffic, and transportation equity. Moreover, different auction methods and the need for the comparisons between them open new research avenues to explore how to and through which technique to create a more efficient market-based tolling system.

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