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THE POTENTIAL OF EMPLOYING CONNECTED VEHICLE TECHNOLOGIES FOR DEMAND MANAGEMENT OF MANAGED LANE FACILITIES

FINAL REPORT

by

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EXCUTIVE SUMMARY

This research explores the potential of employing Connected Vehicle (CV) technologies for demand management of managed lane (ML) facilities. More specifically, we envision CV technologies being adopted to 1) produce rich real-time traffic information, such as travel time variability and reliability as well as pricing variability (if applicable); and 2) disseminate such information to approaching travelers. Such information would likely affect travelers' propensity of choosing MLs and thus the usage rate and the traffic conditions of the MLs and the general-purpose lanes (GPLs). As the market availability of connected and autonomous vehicles (CAVs) is prognosticated by 2020, the potential impact of CAV technologies on effective demand management is worth investigating (*3*).

Priced Managed Lane (ML) facilities have been advocated to effectively mitigate traffic congestion and their number has increased from 14 to 24 in the past five years alone (*4*, *5*). MLs include high-occupancy vehicle (HOV) and high-occupancy toll (HOT) lanes, which are dedicated and restricted lanes that operate in a relatively closed and controlled environment. Despite the prevalence of MLs in the US, there are no rapid HOV to HOT conversions due to public opposition, double taxation and equity concerns (*6*–*8*). It is possible that sometimes travelers may not receive expected benefits from MLs due to uncertainties in traffic such as a traffic accident that is not reflected by the time display. In view of this, we argue that innovative pricing strategies could be explored to boost public acceptance of priced MLs and at the same time help achieve their design objective.

We propose an alternative pricing strategy via an option of Travel Time Refund (TTR). When choosing to pay for MLs, users are provided an opportunity to purchase an additional TTR, which ensures them a certain amount of travel time savings. The cost of TTR is always less than the actual toll. If users did not experience the "insured" travel time savings due to unforeseen circumstances, they would be refunded the toll amount but not the additional cost of TTR.

This study provides a discussion of the implementation issues of TTR and the potential of using CVs to help achieve the vision. We envision CVs to enhance our existing information provision capabilities by providing richer real-time information. The feasibility of utilizing existing road infrastructure, i.e. traffic signs, toll transponders, tollbooths etc. to accommodate the new pricing technology is also considered. The following potential implementation issues of the refund option were discussed:

- Information Provision: Previous research indicates that the driving behavior is affected by not only the mere provision of information but also the actual content. A combination of static and dynamic message signs can be used to provide rich and relevant information to the drivers.
- Toll Collection Technologies: The existing toll transponder technology that includes a switchable feature can be used to distinguish the users who choose to pay for TTR with those who choose to pay only the toll.
- Measurement of Actual Travel Time: The actual travel time plays a key role in determining the refund and can be measured using loop detectors, toll tag transponders, Dedicated Short Range Communications and Bluetooth technologies.

- Calculation and Processing of Refund: The calculation of refund happens at the back end based on a pre-determined pricing algorithm. The refunds will be automatic and posted to the card associated with the transponder account on file.
- Safety and Human Factors: The information provided through visual, auditory or haptic messages on CVs should be legible and easily comprehensible by a driver in a moving vehicle and not negatively influence driver behavior.

CVs may not be utilized to address all the aforementioned implementation issues but play a significant role in information provision, measurement of travel time and safety and human factors. A simulation analysis was performed to determine the impact of information provision on the choice probability of individual travelers. The information from Katy Freeway in Houston, TX was used as reference to generate a series of scenarios involving different roadway capacities. The results indicated that the proportion of ML users increases with increase in market penetration of CVs.

Future research includes investigating the calculation of the actual refund by analyzing the various factors that could possibly influence the risk potential. The impact of the refund option on toll rate and generated toll revenue should also be evaluated. The financial feasibility and implications of deploying the TTR option needs to be explored.

1 INTRODUCTION

This research explores the potential of employing Connected Vehicle (CV) technologies for demand management of managed lane (ML) facilities.

The use of information and communication technologies (ICT) has brought and is continuously bringing innovative approaches to transportation infrastructure ranging from intelligent transportation systems (ITS) to the deployment of connected and automated vehicles (CAVs). Fully automated vehicles are expected to perform all driving activities including making critical safety decisions while connected vehicles enable wireless communication among vehicles, infrastructure and passenger's personal devices (*1*, *2*). As the market availability of CAVs is prognosticated by 2020, the potential impact of CAV technologies on effective demand management is worth investigating (*3*).

Priced Managed Lane (ML) facilities have been advocated to effectively mitigate traffic congestion and their number has increased from 14 to 24 in the past five years alone (*4*, *5*). MLs include high-occupancy vehicle (HOV) and high-occupancy toll (HOT) lanes, which are dedicated and restricted lanes that operate in a relatively closed and controlled environment. Despite the prevalence of MLs in the US, there are no rapid HOV to HOT conversions due to public opposition, double taxation and equity concerns (*6*–*8*). It is possible that sometimes travelers may not receive expected benefits from MLs due to uncertainties in traffic such as a traffic accident that is not reflected by the time display.

In view of this, we argue that innovative pricing strategies could be explored to boost public acceptance of priced MLs and at the same time help achieve their design objective. We propose an alternative pricing strategy via an option of Travel Time Refund (TTR). When choosing to pay for MLs, users are provided an opportunity to purchase an additional TTR, which ensures them a certain amount of travel time savings. The cost of TTR is always less than the actual toll. If users did not experience the "insured" travel time savings due to unforeseen circumstances, they would be refunded the toll amount but not the additional cost of TTR. A stated preference survey was conducted in 2014 in the Phoenix metropolitan area to gauge the travelers' interest toward the refund option and elicit their choices of ML usage under various trip distance scenarios. An exploratory and statistical analysis of the survey responses revealed that travelers are interested in the TTR option. More information on the survey data and associated statistical analyses is beyond the scope of the present paper and the readers are referred to our previous work (*9*, *10*).

The deployment of ICT enables vehicle-to-infrastructure and vehicle-to-vehicle communications and opens various possibilities to information provision and implementing alternative pricing technologies. We envision CV technologies being adopted to provide richer and real-time information about the MLs, such as travel time variability and reliability as well as pricing variability (if applicable), to approaching drivers. Such information would likely affect travelers' propensity of choosing MLs and thus the usage rate and the traffic conditions of the MLs and the general-purpose lanes (GPLs).

The objective of this report is to provide a discussion of the implementation issues of TTR and the potential of using CVs to help achieve the vision. Potential implementation issues include information provision to connected and non-connected vehicles, distinction between toll-only and refund customers, measurement of actual travel time, refund calculation and processing and safety and human factors issues. CVs may not be utilized to address all the aforementioned implementation issues but play a significant role in information provision, measurement of travel time and safety and human factors. For the remainder, chapter 2 provides a comprehensive review of the state of the art practices relevant to the potential implementation issues of TTR. A discussion of the implementation issues of CVs in various stages of toll collection is provided in chapter 3. Simulation analysis presented in chapter 4 will investigate the potential of employing CV technologies for demand management of ML facilities with the goal of improving ML efficiency and effectiveness. Specifically, we will focus on evaluation of travelers' choice probabilities of MLs under various scenarios of traffic conditions and information provision schemes (b) possible impacts of changed ML choice propensity on travel time variability under saturated traffic conditions and (c) determination of the minimal market penetration required.

2 LITERATURE REVIEW

This study provides a discussion of the implementation issues of a new and innovative pricing strategy TTR and the potential of using CVs to help achieve this objective. We envision CVs to enhance our existing information provision capabilities by providing richer real-time information. The feasibility of utilizing existing road infrastructure (traffic signs, toll transponders, tollbooths etc.) to accommodate the new pricing technology is also considered. A brief review of literature in these areas is discussed in the following subsections.

2.1 INNOVATIVE PRICING STRATEGIES

Congestion pricing is currently implemented in some states in the U.S for effective transportation demand management despite public opposition, double taxation and equity concerns. CAVs provide the tolling agencies the flexibility to explore innovative and alternative pricing strategies such as auction based tolling (*11*), that could potentially alleviate the negative concerns towards tolling and generate higher revenue. In view of this, we propose an alternative pricing strategy via the option of TTR. When choosing to pay for MLs, users are provided an opportunity to purchase an additional TTR, which is a type of insurance that ensures them a certain amount of travel time savings. The cost of TTR is always less than the actual toll. If the users did not experience the “insured” travel time savings due to unforeseen circumstances, they would be refunded the toll amount but not the additional cost of TTR. Our previous study on the exploratory and statistical analyses of a stated preference survey revealed that TTR could make the HOT facilities more appealing (*9*, *10*).

2.2 CONNECTED AND AUTOMATED VEHICLES (CAVS)

Connected and Automated Vehicles (CAVs) are expected to revolutionize our transportation in the very near future with companies like Google, Tesla, Uber etc. already testing their vehicle prototypes. In the last year alone, the number of states that enacted legislations for their testing in the US have increased to 33 from 20 (*12*). Researchers and forecasters prognosticate achieving Level 4 automation by 2045 (*13*). Public attitude and perception are crucial for the success of these emerging technologies. Previous research based on surveys across the globe found positive interest from the respondents who are both familiar and unfamiliar with CAV technologies (*14*).

Existing literature suggests the deployment of CAVs could potentially support the travel demand management efforts by significantly reducing congestion (*15*, *16*). The success of CAV technologies to improve traffic conditions depends on the cooperation among all the connected environments and travelers, and their trust in the technology. A recent simulation study demonstrated that the absence of cooperation between travelers and technology led to an increase in traffic congestion (*17*). More research needs to be done in this area before postulating any theories, but the principles of behavioral economics, cognitive and social psychology and game theory could be implemented in the type of information provided to encourage cooperation among the travelers. Previous studies in behavioral economics revealed that positive framing yields greater cooperation than negative framing (*18*). In addition, social approval (visibility of other people’s contributions) encourages cooperation (*19*).

2.3 INFORMATION PROVISION

The use of CAVs to implement TTR is anticipated to enhance the information provision capabilities through the vehicle-to-vehicle and vehicle-to-infrastructure communications. There is considerable research on *a priori* information about travel time influencing the travelers' propensity of route choice (*20–22*). In addition to the actual content of the information provided, travelers' behavior is also affected by the mere presence of the information. As far as actual content is concerned, studies have shown that the provision of expected travel time alone does not significantly influence the route switching behavior (*23*). In addition to the expected travel time, including historical information like range and variability (median, standard deviation etc.) of the travel time changes the travelers' choice behavior (*24*, *25*). Some studies showed that increased information can produce adverse outcomes (*26–30*). CV technologies could be used to effectively manage the optimum amount of information as well as the information content provided to the travelers. In the state of practice, traffic information is commonly provided by the roadside Advanced Traveler Information Systems (ATIS), on dynamic message signs, upstream to the ML facility. Information shown by such systems are constrained by the size of the signs and travelers' cognitive abilities to perceive and process the information in passing. These limitations could potentially be overcome by the use of CV technologies by pushing information to the on-board units and presenting the information as visual messages on the in-vehicle display or as auditory messages. The in-vehicle display could present information in various forms that can be easily comprehended by the drivers. The information could also be displayed for a sufficiently long enough time for travelers' to fully process the information. Auditory messages could augment the visual messages and capture the quick attention of the driver without necessarily distracting them.

2.4 REAL-TIME INFORMATION

CV technologies can help produce real-time information and increase the accuracy of assessing roadway traffic conditions (*31*). Previous studies have shown that providing information such as travel time variability and reliability as well as pricing variability (if applicable) affects the travel behavior (*24*). CV technologies could help provide such relevant information real-time. This real-time information and traffic conditions can effectively be utilized to potentially provide real-time vehicle route guidance systems (*32*).

2.5 ROAD INFRASTRUCTURE

The feasibility of utilizing existing infrastructure for toll collection and traffic signs without having to necessarily revamp the entire system is worth investigating. Electronic toll collection (ETC) systems are currently in use nationwide with the exception of a few manually operated toll booths on-site that accept either only cash or card payments. These ETC systems eliminate the need for the drivers to stop at the tollbooths and enhance the efficiency of traffic. CV technologies which enable vehicle-to-vehicle and vehicle-to-infrastructure communications open doors to devise innovative but practically feasible toll schemes including but not limited to TTR, auction toll, dynamic toll rates based on network and travel demand attributes and drivers' willingness to pay (*9–11*, *33*). Until the full penetration of CAV-enabled vehicles, toll payers are identified using the EZ-tags usually installed on the front windshield of the vehicle. The information exchanged between the EZ-tag installed in the car and a Dedicated Short Range Communications (DSRC) beacon installed on the overhead signs of the roadway enables the identification of entry and exit points for travel time and toll calculation (*34*).

Although the CAVs are expected to have on-board display and audio units, until their full market penetration, there is still the need for traditional signage on the road to convey messages to the road users. The state of the practice is the use of hybrid signs, which are a combination of the conventional retroreflective static sign and one or more small light emitting diode message panels that display dynamic information like travel time, toll costs, route diversion, accident and other emergency information. The static portion of the sign includes information about the location and the message panels convey varying travel time and toll cost information based on the time of day (*35*).

3 TTR IMPLEMENTATION CONSIDERATIONS

While the innovative pricing mechanism of TTR is theoretically very appealing, feasibility and other practical implementation issues cannot be ignored. The existing infrastructure may need to be modified or completely revamped to accommodate the introduction of such new technologies. The type of information provided utilizing the CAV technologies and the distinction between HOT and TTR users are some of the issues that need to be carefully investigated. Potential implementation issues include information provision to both connected and non-connected vehicles, distinction between toll-only and refund customers, measurement of actual travel time, refund calculation and processing and safety and human factors issues. These issues are discussed in detail in the following sections.

3.1 BACKGROUND

Previous studies have shown that the driving behavior is affected by not only the mere provision of information but also the actual content of the information. The state-of-the practice ATIS or dynamic message signs can be used to provide information related to the refund pricing to the travelers. Hybrid signs which are a combination of static and dynamic message signs can be used to provide information about travel time and toll cost (HOT and TTR) to the drivers as shown in Figure 1.

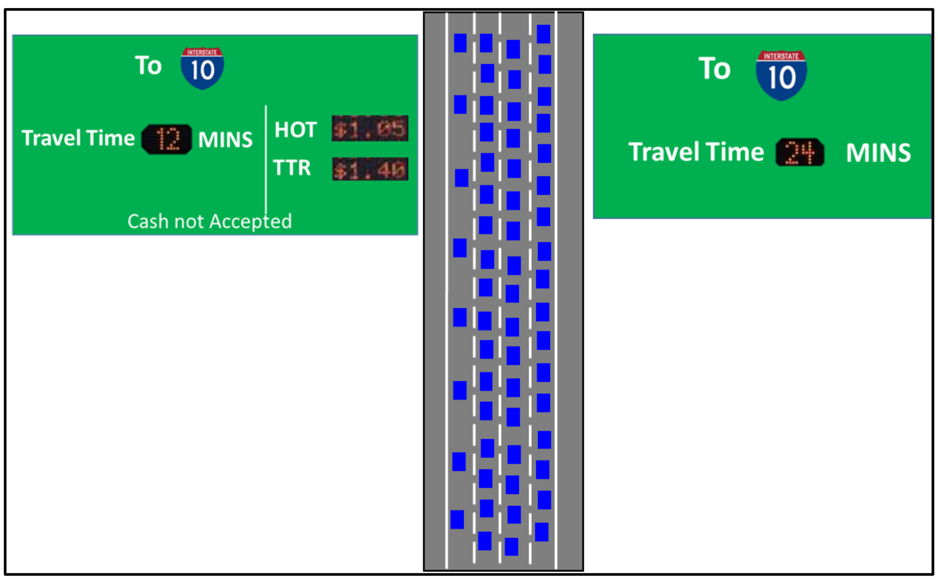

Figure 1 Sample Layout of Road Network with Signage for Refund Option

The travel time displayed on these signs is estimated using the information obtained from loop detectors, Bluetooth and Wi-Fi enabled technologies etc. as described Section 4.3. This travel time is updated at a certain time interval (2 minutes, 5 minutes etc.) based on the agency standards. The amount of information displayed on the signs is constrained by their size and the driver's cognitive abilities to comprehend it in passing. On the other hand, CAVs are not necessarily subject to this limitation as they are expected to be able to receive, process, and display more diverse and more relevant information in a real-time manner. The following are some of the potential types of information that can be displayed on-board an equipped CV:

Travel time and savings of other CVs: Real time information of travel time and potential savings in time of other CVs can be provided to motivate the drivers to purchase the TTR in accordance with the previous research on social learning (*18, 19*).

Return of Investment: The provision of the travel time and the toll cost alone does not mean anything to the travelers unless they are familiar with the value for their money. The on-board messages can be used to provide information about the return of investment or benefit to cost ratio, which is expected to be a motivator to consider the HOT and TTR options.

Recommended action and the confidence level: Previous studies have shown that learning and experience affect the travel behavior. The travelers may be hesitant to invest in the new pricing strategy and providing some recommended information on purchasing the HOT/TTR option may be encouraging. This will relieve them from second-guessing that is not uncommon when they are left on their own to decide. Airline tickets purchase site Kayak provides a forecast of how likely the ticket prices are to go up or down over the next seven days for a given destination and dates (*36*). It also provides a recommendation of whether to buy the ticket now or wait along with a confidence level (number or percentage of statistical accuracy). Similarly, the CVs could provide a percentage indicator of how likely it is for the drivers to stay within the estimated travel time. A recommendation of whether to choose the HOT/TTR option along with a confidence level can also be included.

The above information can be presented using a combination of auditory and visual messages to ensure both the comprehension and safety of the drivers.

3.2 TOLL COLLECTION TECHNOLOGIES

In the proposed refund strategy, the traveler has the option of using the toll road without choosing to pay the additional premium for the TTR. There should be a way to differentiate the HOT and TTR users. For CVs, this could be a choice made by the click of a button through an application enabled by the on-board units. For non-connected vehicles, this can be achieved by making minor modifications to the existing transponder technology. A toll transponder with a switchable feature called EZ-Pass Flex currently being used on the I-95/495 Express Lanes in Virginia (*37*) is shown in Figure 2. This transponder lets a traveler utilize the HOV discount if there are more than two or three people in the car by sliding the transponder switch to one side to indicate the “HOV ON” status. If there is only one person in the car, the switch is moved the other way to indicate travel at the posted toll rate. The same technology could be utilized to indicate whether the traveler wishes to use the HOT or the TTR option. If they wish to pay the additional premium, they will switch the transponder switch to TTR and if not they leave it at the default HOT. The transponder will work as the standard EZ-Pass on toll roads, which necessarily do not have a TTR option irrespective of the switch position.

Figure 2: Illustration of EZ-Pass for Refund Strategy (Source: https://www.ezpassva.com/EZPages/New-Flex.aspx).

3.3 MEASUREMENT OF ACTUAL TRAVEL TIME

Historically, the travel time was measured using license plate matching, attaching mechanical devices to odometers or using GPS recording devices (*38–41*). Probe vehicles, which drive through the network at various times, are also in use despite the accuracy concerns with a relatively low sample size. With the advent and wide spread use of Automatic Vehicle Identification (AVI) systems, travel times are now measured using toll tags and Bluetooth technology (*34*). AVI systems use radio-frequency identification (RFID) technology to enable communication between the in-vehicle transponder and roadside unit for travel time or toll calculations. These systems cannot be used when there are no toll roads or the existing infrastructure does not support the technology. Most of the transportation agencies use the traditional inductive loop detectors, which are typically installed per mile in every lane of the freeway and collect speed, volume and occupancy information. The data is gathered at a pre-determined frequency (for example every 20 seconds) and can be aggregated into 5, 15 or 60 minutes based on the requirements of the individual agency. The travel time between stations is calculated based on speed and distance, where missing data is often imputed by statistical means, spatial interpolation or trajectory methods. Loop detectors are the primary source of the travel time displayed on the physical hybrid signs and includes information from all the vehicles passing through them.

A toll tag transponder is required for toll collection and identification until the full penetration of CVs. Upon complete market penetration, CVs can choose their HOT/TTR option on-board without the need of a transponder. For vehicles (both CV and non-CVs) equipped with a toll tag transponder, the toll tag reader (installed on the overhead sign gantry or the side of the road) receives the signal from the transponder and the travel time between two roadside units is estimated based on the time difference and distance between them. The processing and estimation of travel time happens at the back end and the current travel time of other CVs within a pre-defined vicinity is displayed on the on-board units of CVs real-time. The transponder-equipped vehicles can also help gather travel time information for the general-purpose lanes. This may only require the additional installation of toll tag readers over the general-purpose lanes.

The information from vehicles equipped with Dedicated Short Range Communication (DSRC) technologies can also be used to calculate travel time for general-purpose lanes. For vehicles not equipped with toll tags or DSRC technologies, Bluetooth sensors can also be used for travel time measurements. A portable Bluetooth sensor installed on the overhead gantry detects the MACID of the personal mobile devices and the time of detection. Similar to toll tag transponders, the travel time is estimated based on the time difference and distance between the Bluetooth sensors.

The information collected from the transponder, Bluetooth and DSRC technologies can be integrated with that obtained from the loop detectors to generate more accurate travel time estimates. This fusion helps in improving the bias in the estimates (if any) from loop detectors due to missing data imputation and help in providing richer information.

3.4 CALCULATION AND PROCESSING REFUND

The determination of the TTR cost, the refund amount and how the refund is processed plays a crucial role in the successful implementation of TTR pricing strategy. The refund could be a full or a partial refund and can potentially be determined based on risk, similar to the insurance rates or premiums for home or auto insurance. Risk is defined as the potential (probability) that someone will make a claim. The insurance rates or premiums are determined based on the premise that the greater the risk, the higher the premium and the lower the risk, the lower the premium. This is likely to maximize revenue generation but may not realistically achieve the operational objective of maintaining free-flow traffic on the toll lanes while maximizing the throughput of the freeway (combined toll and GP lanes). This can be achieved by dynamically varying the toll rate in response to changing traffic conditions over time (*42–45*). For example, the toll rates on I-394 HOT lanes in Minnesota, I-15 in San Diego and Katy Freeway in Houston among others are adjusted based on the observed traffic density to be able to maintain free flow traffic conditions. Recent studies have suggested iteratively adjusting the pricing of toll lanes in real-time based on lane occupancy and the motorist's willingness to pay through a reactive self-learning approach (*46*, *47*). Various innovative pricing schemes based on anticipated or predicted congestion (*48*), variation in space (*49*), travel characteristics or attributes (*33*) have also been proposed. More research needs to be done in this area to formulate a pricing strategy for the TTR option based on current practice and proposed techniques. The auto insurance premiums are typically determined based on the driver demographics, driving record, vehicle make, model and its safety features (*50*). Similarly, the refund rates can potentially be determined based on historic travel times, congestion levels, crash history and weather.

The calculation and processing of refund will potentially be automatic at the back end with the use of technology. Unlike the current practice in majority of insurance- and consumer- related claims, the users need not go through the strenuous process of manually filing a claim and communicating with multiple agents until its final resolution, which may take up to several days if not months or more. The transponder has the toll location information, from which the recorded experienced travel time can be compared with that displayed on the VMS signs or through on-board units to determine the refund eligibility based on the position of the transponder switch. The refund can either be posted to the credit card/debit card /bank account on file for the transponder account consistent with the current practice in the retail or consumer industry. If chosen by the user, it can also be posted as a credit on the transponder account, which could be used for future transactions.

3.5 SAFETY AND HUMAN FACTORS

CVs and fully automated vehicles result in a reduced driver workload allowing them to involve in secondary tasks like in-vehicle entertainment, work etc. Although the degree of this involvement depends on the level of automation, it poses a potential safety hazard when there is a vehicle automation failure. Although existing literature based on simulated studies showed decreased attention to the road ahead due to secondary tasks, they proved that drivers paid increased attention if the situation demanded like heavy traffic (*51*, *52*). Another study determined that age does not impact the switch from automated to manual driving control when evading an obstacle indicating older drivers are able to handle maneuver changes as well as younger drivers (*53*).

The information provided should be legible and easily comprehensible by a driver in a moving vehicle and not negatively influence the driver behavior. The connected vehicles with their onboard display units support the selection of sensory modalities (visual or auditory) for information provision. Research suggests the use of visual messages for presenting complex information that does not call for immediate attention and is not safety-critical. Auditory messages are used for short messages that require quick or immediate action from the driver. Previous research suggests improved operator/driver performance when information is presented using a combination of visual auditory and haptic messages (*54*). This combination can be utilized to provide travel time, statistical confidence and information about the potential return on investment or benefit–cost ratio of using MLs to the drivers. The auditory messages could reveal the magnitude of the potential savings while symbolic messages that vary in size with the magnitude of the savings can be displayed on the on-board unit. The potential saving information is a little complex that cannot be presented using simple tones, earcons or auditory icons and would require the use of speech messages for greater legibility and faster comprehension. Haptic messages provide information to the end user utilizing the sense of touch in a user interface and this technology is currently being tested by one leading vehicle manufacturer (*55*). The timing that this information is provided could play a significant role in safety and human factors that needs to be further investigated.

The introduction of managed lanes involves reducing the width of the median, left or right shoulder or eliminating them altogether due to space constraints. The type of barrier used determines the width of the buffer required for the separation of managed lanes from general-purpose lanes. The barrier could be physical (pylons or concrete) with or without intermediate access points or a non-physical painted stripes or solid double-white lines with or without enforced access. Existing safety studies on HOT and HOV lanes suggest fewer crashes are associated with wider lanes and buffer widths. Higher number of access points are associated with increasing crashes due to excessive weaving between the managed and general-purpose lanes (*56*). The addition of new managed lanes should comply with the geometric design criterion while considering the safety tradeoffs.

4 SIMULATION

4.1 BACKGROUND

The models developed by Ben-Elia and Shiftan (*24*) has been identified for further analysis from the comprehensive literature review presented in the previous section. In this paper, the survey respondents are presented with a choice of two routes, fast (F) and Slow (S) with an average travel time of 25 and 30 minutes. The estimated travel time information is provided by the advanced traveler information systems with possible ranges of ±5 or ±15 minutes for each route. The three possible scenarios are fast & safe, fast & risky and low risk. A total of 49 participants were recruited for the survey and were randomly divided into informed group (N= 24) and non-informed group (N=25). All the participants were presented with all the three traffic scenarios mentioned earlier and each scenario included making 100 route choices. The informed group received information about the estimated travel time range. This travel time has a variation of 0-3 minutes around the mean so that the information is not the same across all the 100 100 choices in a scenario. After the choice is made, the actual travel time is provided to the respondents. This travel time is drawn from a uniform distribution of the estimated travel time range. The non-informed group does not receive the estimated travel time but are provided the actual or feedback travel times similar to the informed group.

A mixed logit model was estimated to determine the factors that impact the route choice behavior. The utility equations of the specified model are as follows:

$$U_S = \beta_{mean}\, Means + \beta_{times}\, times$$

$$U_F = \beta_{mean}\, Meanf + \beta_{timef}\, timef + \beta_{lrisk}\, lrisk + \beta_{frisky}\, frisky + \beta_{exl}\, exl + \beta_{exh}\, exh + \beta_{stick}\, stick + \beta_{cwa}\, cwa$$

Where,

$Means$ = Mean travel time of the slow route

$times$ = actual/feedback travel time of the slow route

$Meanf$ = Mean travel time of the fast route

$timef$ = actual/feedback travel time of the fast route

$lrisk$ = scenario is low risk

$frisky$ = scenario is fast & risky

exl = low experience reflecting choices within the first 10 trials

exh = high experience reflecting choices in the last 50 – 100 trials

$stick$ = variable denoting repetition of previous behavior

cwa= cumulative weighted average of preceding choices

β's denote the coefficient estimates of the above variables

Three variants of the above model were estimated with different specifications of the estimated travel times. The first model uses the average of the provided travel time ranges for the estimated travel time. The second variation uses the difference between the estimated and provided travel times. If this difference is positive, it is termed as gain and loss otherwise. The third variation of the model replaces the range of the estimated travel time with the variance.

4.2 DATA GENERATION

Katy freeway in Houston, TX was used as a reference for the generation of data. The average travel time on Managed Lanes (MLs) and General Purpose Lanes (GPL) of Katy Freeway is 10 and 15 minutes respectively. The available travel time ranges were assumed to be ±2 or ±5 minutes. The vehicle type identifies the informed and non-informed groups i.e. if the vehicle is a connected vehicle or not. Informed groups are all connected or autonomous vehicles whereas non-informed are the regular passenger car vehicles without any connected technologies. For connected vehicles, the estimated travel time ranges are randomly generated with a variability of 0-3 minutes around the mean travel time. The actual travel times are then uniformly generated from the range of the estimated travel times. For non-connected vehicles, the estimated travel time is the mean travel time and the actual travel time is obtained similar to the connected vehicles. This data is generated for varying percentages of connected vehicles in increments of ten until saturation and for varying roadway capacities (1000, 1200, 1400, 1600 and 1800 vph). The scenarios used are low risk, low risk – fast & risky and fast & safe to low risk.

4.3 ANALYSIS

The data for low risk, low risk – fast & risky and fast & safe to low risk scenarios were generated as discussed in the previous section. The coefficient estimates from the model developed by Ben-Elia and Shiftan (*24*) were used in the model. The utility equations for the model are as follows:

Connected Vehicles

$$U_{GPL} = 1 * Means - 0.09 * times$$

$$U_{ML} = 1 * Meanf - 0.13 * timef + 4.73 * lrisk + 1.75 * frisky$$

Non-connected vehicles

$$U_{GPL} = 1 * Means - 0.21 * times$$

$$U_{ML} = 1 * Meanf - 0.24 * timef + 0.76 * lrisk + 0.13 * frisky$$

Based on the choice probabilities, the percentage of respondents choosing the MLs is calculated for each of the low risk, low risk – fast & risky and fast & safe to low risk scenarios. The information presented in the following tables represents the average across three runs.

The percentage of ML users for varying road capacity and connected vehicle market penetration for the low risk scenario are presented in Table 1.

Table 1: Percentage of ML Use for Low Risk Scenario

Market Penetration	Roadway Capacity				
	1800	1600	1400	1200	1000
10	7.19	6.67	6.74	6.94	6.90
20	11.28	10.96	11.05	11.56	11.90
30	15.81	15.13	14.95	16.11	15.33
40	19.20	18.54	20.29	19.31	19.07
50	23.04	22.92	22.05	23.94	23.93
60	27.54	26.81	27.60	27.67	25.90
70	30.31	30.92	31.40	31.67	32.40
80	35.76	36.31	35.79	33.67	34.50
90	39.22	39.33	38.98	38.56	37.33
100	44.19	42.38	42.67	43.11	43.60

There is an increased proportion of ML users with increasing percentage of connected vehicles for different roadway capacities. When all the vehicles are connected, 42- 45% of the road users choose the MLs over the GPL lanes.

The percentage of ML users for varying road capacity and connected vehicle market penetration for the low risk to fast & risky scenario is presented in Table 2. When there is shift in the scenario from low risk to fast & risky due to an incident or road closure, the proportion of ML usage still increases with the market penetration of connected vehicles across different roadway capacities. The proportion of ML users varies between 23 and 30 percent for capacities between 1800-1000 vph at full market penetration of connected vehicles.

Table 2: Percentage of ML Use for Low Risk - Fast & Risky Scenario

Market Penetration	Roadway Capacity				
	1800	1600	1400	1200	1000
10	5.22	5.02	4.10	4.44	5.00
20	6.76	6.81	6.10	6.69	8.37
30	8.93	8.81	8.76	9.08	10.37
40	11.31	11.29	11.31	11.22	12.63
50	13.17	11.96	13.00	13.11	16.10
60	14.57	15.98	14.57	15.19	20.37
70	16.83	17.63	16.86	17.28	20.63
80	18.74	19.35	19.12	19.39	24.03
90	21.48	21.73	21.86	21.00	26.97
100	23.00	22.94	23.36	23.58	29.27

The percentage of ML users for varying road capacity and connected vehicle market penetration for the fast & safe to low risk scenario are presented in Table 3.

Table 3: Percentage of ML Use for Fast & Safe - Low Risk Scenario

Market Penetration	Roadway Capacity				
	1800	1600	1400	1200	1000
10	4.89	4.52	3.90	4.47	4.57
20	6.00	6.60	6.71	6.56	6.37
30	7.31	8.25	8.31	7.53	9.10
40	10.04	10.92	10.55	10.28	10.93
50	12.30	11.58	13.00	12.25	12.20

60	13.43	14.81	14.07	12.94	14.63
70	16.35	15.79	16.40	14.75	16.30
80	17.65	18.25	19.17	17.67	17.17
90	20.80	20.81	19.38	19.56	20.57
100	22.28	22.15	21.79	22.42	21.17

The proportion of ML users is similar to the low risk to fast & risky scenario for higher capacities 1800 and 1600 vph but lower for other capacities. The proportion of ML users varies between 23 and 30 percent for capacities between 1800-1000 vph at saturated connected vehicle market penetration.

5 CONCLUSIONS

This study provides some insights into the implementation considerations of an innovative pricing scheme for managed lanes, namely the travel time refund option and the potential of using connected vehicles for such implementation. The TTR provides an additional incentive to the drivers to pay for MLs by insuring their travel time and refunds their toll cost if they do not arrive at their destination within the specified travel time savings. Exploratory and statistical analyses of the responses from a stated preference survey found that travelers are interested in the refund option. Discussions on 1) information provision, 2) toll collection, 3) measurement of actual travel time, 4) refund calculation and processing, and 5) safety and human factors are provided in this report. CVs can potentially be applied to provide richer real-time information including travel time savings and return on investment that motivate the travelers to choose HOT and TTR options.

This study revealed that HOT lanes with a refund option are technically feasible to implement using the existing toll tag transponder technologies. Additional investigation is needed on formulating a robust pricing strategy to determine the actual toll costs. Existing refund processing practices from the retail and consumer industry can be applied to process the refunds. Highly automated driving does not potentially have a detrimental effect on driver performance and safety. With CVs, a combination of visual, audio and haptic messages can be utilized for information provision without affecting the driver behavior. A simulation analysis with information from Katy Freeway in Houston, TX was used to generate a series of scenarios involving various flow rates. The model identified in the literature review was applied on this data with reasonable assumptions to obtain ML usage and the results indicate that the proportion of ML users increases with increase in market penetration of connected vehicles.

Future research includes investigating the calculation of the actual refund by analyzing the various factors that could possibly influence the risk potential. The impact of the refund option on toll rate and generated toll revenue should also be evaluated. The financial feasibility and implications of deploying the TTR option needs to be explored.

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