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Comparing Pricing Mechanisms of Managed Lanes: Performance Assessment of PR-22 Dynamic Toll Lanes

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16. Abstract A performance assessment and willingness-to-pay (WTP) analysis were conducted of the reversible dynamic toll lanes (DTL) of freeway PR-22 in Puerto Rico. This is the first managed lane facility of its kind in a toll freeway in Puerto Rico. Toll transactions from the year 2019 were used to calculate seven performance measures to assess the impact of the managed lanes on travel times and vehicle speeds on the 12 km-long (7.7 mi) segment. The results demonstrate that the dynamic pricing algorithm behaves as expected, increasing the price for the DTL as traffic increases and vehicle speeds decrease on the facility, and provided satisfactory performance for the conditions at PR-22. The DTL provided an average travel time savings of 7 minutes and enhanced travel time reliability when compared with the general toll lanes (GTL) during the morning peak period. Compared to six other managed lane facilities in the U.S., the results from the PR-22 DTL show higher travel time savings and reliability. A survey of PR-22 users was conducted to estimate their willingness-to-pay (WTP) and their attitudes and perceptions associated with the quality and usage of the DTL. The aggregate analysis of PR-22 users using the Van Westerdorp Price Sensitivity Meter resulted in a WTP range for the DTL of \$1.00 to \$2.79, which is less than the \$4.95 maximum toll charged for the managed lane facility. Even though the maximum price exceeds their WTP, the level of congestion in the GTL during peak periods still motivates users to pay the extra fee for the DTL outside of their preference. A regression analysis found that the factors that significantly reduce the WTP of the freeway users include subjects from higher income levels, higher ages, and females. As stated by freeway users, the congestion in the GTL is the main factor that influence them to use the DTL. Therefore, a recommendation to increase the usage of the PR-22 DTL is to provide commuters with relevant information about the real-time benefits of the DTL. The implementation of a high-occupancy vehicle (HOV) policy for the freeway corridor should also be studied. A HOV policy could promote ridesharing on the corridor while providing economic relief and enhancing the equity of the toll freeway by reducing or eliminating the premium toll fee of the managed lanes to those commuters.			
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Abbreviations and Acronyms

AADT	Annual Average Daily Traffic
AASHTO	American Association of State Highways and Transportation Officials
ATIC	Availability of Toll to Impact Congestion
DOT	Department of Transportation
DOW	Day of week
DI	Dominance Indicators
DTL	Dynamic Toll Lanes
EB	Eastbound
Eq.	Equation
FFS	Free flow speed
FHWA	Federal Highway Administration
GPL	General Purpose Lanes
GTL	General Toll Lanes
HOT	High-Occupancy Toll
HOV	High-Occupancy Vehicle
IPP	Indifference Price Point
IRB	Institutional Research Board
km	Kilometers
MADT	Monthly Average Daily Traffic
mi	Miles
ML	Managed lanes
mph	Miles per hour
NICR	National Institute for Congestion Reduction
OPP	Optimum Price Point
PMC	Point of Marginal Cheapness
PME	Point of Marginal Expensiveness
PPP	Public-Private Partnership
PR	Puerto Rico
PTI	Planning Time Index
PTIB	Planning Time Index Benefit
SJMA	San Juan Metropolitan Area
ST	Speed Threshold
SOV	Single-occupancy vehicle
TAMU	Texas A&M University
TTI	Travel Time Index
TTS	Travel Time Savings
UPRM	University of Puerto Rico at Mayagüez
U.S.	United States
VOR	Value of Reliability
VOT	Value of Time
vpd	Vehicles per day
vph	Vehicles per hour
VWPSM	Van Westendorp Price Sensitivity Meter
WB	Westbound
WTP	Willingness-to-Pay

Executive Summary

Active demand management strategies, such as managed lanes, are promoted on freeway corridors as a congestion mitigation solution. Managed lanes have been linked to improved travel time reliability and vehicle speeds, and enhanced efficiency on the general-purpose lanes (GPL). This report presents the performance assessment conducted of the first dynamic toll lane (DTL) facility established in freeway PR-22 in Puerto Rico.

Seven performance measures were calculated using toll transaction data from the year 2019 to evaluate and understand the efficiency of the managed lanes on PR-22. The PR-22 DTL is a 12 km-long (7.7 mi) facility with a reversible operation on two median lanes. Traffic volumes, vehicle speeds, and the dynamic toll price paid by the freeway users were used to calculate the Travel Time Index (TTI), the Travel Time Savings (TTS), the Planning Time Index (PTI), the Planning Time Benefit (PTB), the Ability of Toll to Impact Congestion (ATIC), the Speed Threshold (ST), and the Dominance Indicators (DI).

The performance measures calculated in this study demonstrate significant benefits on travel times, travel time reliability, and vehicle speeds provided by the PR-22 DTL and the potential impact for congestion reduction in the freeway corridor. The traffic counts indicate there is a higher usage of the DTL during the morning period than during the afternoon. The traffic counts and average speeds during the morning peak period demonstrate the dynamic pricing algorithm behaves as expected, increasing the price for the DTL as traffic increases and vehicle speeds decrease on the median lanes. The values of the TTI and PTI performance measures show reduced travel times and enhanced travel time reliability for the DTL users. With a TTI value of 1.23, the DTL provides an average reduction in travel time of approximately 7 minutes for the morning peak period. Similarly, the DTL has a PTI value of 1.68 against a 3.96 value for the general toll lanes (GTL) during the morning peak.

Economics-related analyses were also performed to incorporate factors from the point of view of the freeway users. An online survey of PR-22 users was conducted to estimate their willingness-to-pay (WTP) and to gather information about their attitudes and perceptions associated with the quality and usage of the DTL. The aggregate analysis of PR-22 users using the Van Westendorp Price Sensitivity Meter resulted in a WTP range for the DTL of \$1.00 to \$2.79. The WTP range lies below the \$4.95 maximum toll charged for the use of the managed lanes. Based on the toll transaction data, the pricing algorithm established a price at or higher than \$2.79 approximately 50% of the time during 2019. Even though the toll of the DTL exceeds their WTP, the level of congestion in the GTL still motivates users to pay the extra fee outside of their preference.

This study was part of a collaborative research project between the Texas A&M University and the University of Puerto Rico at Mayagüez as part of the National Institute for Congestion Reduction (NICR) activities. The goal of the NICR project was to evaluate the performance of the variable and dynamic congestion pricing approaches on traffic conditions to assess if any provide enhanced traffic management benefits. Data from seven freeway facilities were obtained and performance measures related to vehicle speeds and traffic volumes were calculated by the two research groups. Burriss et al. [2021] published the results from two variable priced and four dynamically priced facilities from freeway corridors located in California, Colorado, Minnesota, and Texas. The results from Burriss et al. [2021] and from this study tend to suggest that the dynamic pricing mechanism provides slightly improved performance than the variable pricing. In general, the results for the TTS and PTIB measures for the PR-22 DTL exhibit better performance and travel time benefits than for the other six managed lanes. However, the overall conclusion indicated in Burriss et al. [2021] is also shared that the sample of managed lane facilities used is somewhat limited to reach a strong inference to establish if one pricing mechanism outperforms the other. Data from other



managed lane facilities in additional jurisdiction should be included in a future research project to expand the results from the NICR project.

The elasticity of the price demand and the value of time was also estimated to assess the interaction between the toll paid and the amount of traffic on the PR-22 DTL. The analysis of the toll transactions resulted in price elasticity of demand values of 1.21 for the morning direction and 1.66 for the afternoon direction. These positive elasticity values, combined with the estimated Value of Time of \$21.47 per hour, obtained from the stated preference experiment, provide evidence of the travel time benefits of the DTL. The higher elasticity result for the afternoon period aligns with the higher Value of Time for the afternoon period found in the literature. As commuters have more urgency in completing their trips during the afternoon, their absolute elasticity and Value of Time values would also tend to be higher.

A recommendation to increase the usage of the managed lanes on PR-22 is to provide freeway users with relevant information about the real-time benefits of using the facility. As stated by PR-22 users, the congestion level in the general toll lanes was the factor that most influenced them to use the managed lanes. Informing the actual travel time savings on the managed lanes could motivate more freeway users to pay the premium fee to gain the travel time benefits for their trips.

Another recommendation is to study the potential benefits of implementing a high-occupancy vehicle (HOV) policy for the managed lanes. The study can simulate potential vehicle occupation scenarios and assess the impacts on the person-carrying capacity of the freeway corridor and the performance effects on the managed lanes. The HOV policy can promote ridesharing while providing economic relief to users or enhancing the equity of the managed lanes by reducing or eliminating the premium toll fee to those users.

1. Research Problem

The vehicle-miles of travel and the length of the highway network have persistently grown in the United States (U.S.) for the last 100 years [BTS, 2020]. Traffic demand increased by 9.2% in the U.S. during the 2010-2018 period. As a result, urban areas have experienced increasing travel times for commuters and higher costs for freight traffic. Congestion refers to the condition of vehicular flow that is saturated due to excess demand on a highway corridor, resulting in increased travel times and network breakdowns. Schrank et al. [2019] estimated a 14% increase in travel delay and a 35% increase in truck congestion costs between the years 2012 and 2019. The 2019 Urban Mobility Report indicates that traffic congestion is becoming worse, with approximately 30-40% of the total delay occurring during the midday and outside of the typical peak hours for cities of all sizes and that 54% of the total delay in large urban areas is on the freeway system [Schrank et al., 2019].

Puerto Rico, a U.S. territory in the Caribbean Region, has also experience worsening traffic congestion problems in the last decades. Puerto Rico (PR) has a population of about 3.19 million inhabitants and 3,515 square miles [U.S. Census, 2019]. Figure 1 shows the vehicle ownership rate in the territory for the period between 2000 and 2010. The motor vehicle ownership rate in Puerto Rico was 661 units per 1,000 people by the year 2010, the 11th highest-ranking worldwide [Macro Economy Meter, n.d.]. From another perspective, Puerto Rico had 91.6 vehicles per kilometer of road by 2010, the 15th highest-ranking worldwide [Macro Economy Meter, n.d.]. The high number of motor vehicles leads to traffic congestion in the road network, especially during peak periods when road users coincide to go to work in the morning or when traveling back home in the evening.

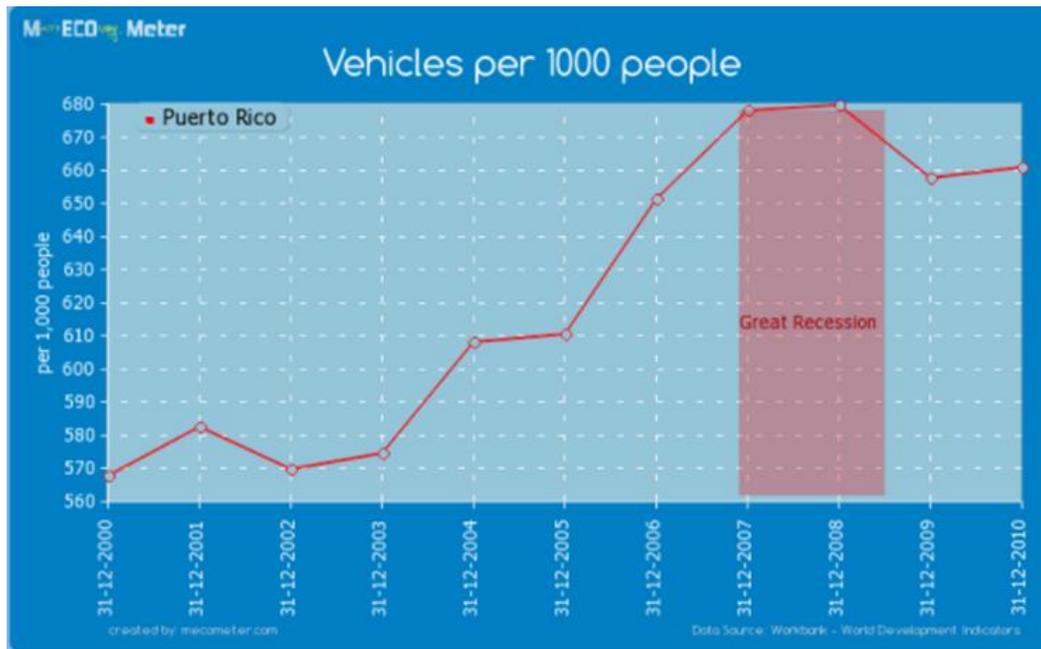


Figure 1 - Vehicles per 1,000 people in Puerto Rico from 2000-2010

(Source: <http://mecometer.com/country/puerto-rico/demographics/>)

Traffic congestion is a daily issue for the residents of the archipelago, particularly for those living and commuting in the San Juan Metropolitan Area (SJMA), with an estimated mean travel time to work of 29.3 minutes for the year 2019 [U.S. Census, 2019]. The 2019 Urban Mobility Report ranks the SJMA in the 24th position of urban areas in the U.S. with 58 hours of annual delay per auto commuter [Schrank et al., 2019].

The problem of traffic congestion on the road network is costing society billions of dollars. The national cost of traffic congestion has risen significantly, from \$15 billion in 1982 to \$179 billion in 2017, for a 1,093% increase [Schrank et al., 2019]. In a similar fashion, the annual cost of congestion in the SJMA was estimated at \$58 million in 1982, compared to \$1.78 billion in 2017, for a staggering 2,965% increase [Schrank et al., 2019].

The times where congestion mitigation strategies focused solely on increasing roadway capacity are fading quickly. Congestion mitigation has shifted to better manage existing facilities for improved sustainability and efficiency [NASEM, 2012]. A broader spectrum of transportation innovations is now favored using active demand management strategies, complete streets, multimodal oriented options, land use planning strategies, smart growth policies, and technological solutions, among others. Managed lanes are one of the innovative solutions related to active traffic management strategies. The Federal Highway Administration [FHWA, 2008a] defines managed lanes as “designated lanes or roadways within highway rights-of-way where the flow of traffic is managed by restricting vehicle eligibility, limiting facility access, or in some cases collecting variably priced tolls.” These facilities provide the flexibility to highway users to decide whether to select its use based on the current roadway conditions, pricing, and lane restrictions [Texas Transportation Institute, 2021]. The expected benefits of managed lanes include improved travel time reliability, increased speed, and efficiency on the general-purpose lanes (GPL), and increased safety when trucks separate from the main traffic flow.

The most common pricing mechanisms used for managed lanes are: Static or Time-of-Day Pricing and Dynamic Pricing. When using the static pricing mechanism, the toll price changes according to the time of the day. As the name implies, the toll price does not consider the existing traffic conditions on the corridor and the change in the toll rate is predetermined from an analysis of the historical traffic flow patterns. In contrast, the dynamic pricing mechanism applies a toll rate that changes considering the prevailing traffic conditions in the corridor. This mechanism requires strategically located sensors on the road to collect real-time traffic data, estimate traffic flow parameters, and establish the toll rate that can maintain the desired performance level in the facility. The dynamic pricing algorithms used to determine the toll levels generally contain minimum and maximum bounds.

This report presents the results from a study that analyzed performance measures for the dynamic toll lane (DTL) facility located in freeway PR-22 in Puerto Rico. The study was part of a collaborative research project between the Texas A&M University (TAMU) and the University of Puerto Rico at Mayagüez (UPRM) promoted by the National Institute for Congestion Reduction (NICR) University Transportation Center (UTC). The overall goal of the NICR project was to evaluate the performance of the two congestion pricing approaches on traffic conditions to assess if the traffic management benefits from dynamic pricing are commensurate to its more resource-intensive implementation compared to static pricing. The research teams had access to large datasets from seven freeway facilities in the mainland U.S. and Puerto Rico to calculate performance measures related to vehicle speeds and traffic volumes to assess the effectiveness of the two congestion pricing strategies. Burris et al. (2021) publish the results from the analysis conducted of two variable priced and four dynamically priced facilities from freeway corridors located in California, Colorado, Minnesota, and Texas.

a. Research Objectives

The general objective of this study was to analyze toll transaction data from freeway PR-22 in Puerto Rico, also known as the José de Diego Expressway, to assess the efficiency of the dynamic pricing scheme on the express lanes. The data collected was analyzed to calculate performance measures and model the effectiveness of the variable toll pricing scheme on reducing congestion for the freeway corridor.

The specific objectives for the UPRM research team were to:

1. Calculate selected performance measures to assess the efficiency of the variable toll pricing mechanism used for the DTL facility in PR-22. The selected measures were the Travel Time Index (TTI), the Travel Time Savings (TTS), the Planning Time Index (PTI), the Planning Time Index Benefit (PTIB), the Ability of Toll to Impact Congestion (ATIC), the Speed Threshold (ST), and the Dominance Indicators (DI). The DI is a new performance measure proposed in this study.
2. Conduct an online survey directed toward users of freeway PR-22 users to obtain frequency and usage factors of DTL users, determine a sociodemographic profile of the freeway users, and estimate the willingness-to-pay (WTP) of freeway users.
3. Analyze traffic flow parameters and toll paid using PR-22 data to estimate the price elasticity of demand and the value of time (VOT) for freeway users.

b. Report Organization

This report is organized into seven chapters. This chapter contains an introduction to the research problem and the study objectives. Chapter 2 presents the methodology with the steps followed to meet the project objectives. Chapter 3 includes the literature review that focused on the topics related to managed lane types, implementation benefits, and descriptions of the selected performance measures. The review also included economics-related topics of the price elasticity of demand and the WTP estimates.

Chapter 4 provides a general description of freeway PR-22, information about the operation of the DTL facility, the description of the toll transaction database, and a discussion of general traffic statistics calculated for the DTL and the general toll lanes (GTL). Chapter 5 discusses the results from the online survey conducted to identify sociodemographic characteristics of DTL users, determine DTL frequency and usage factors and estimate the WTP of the PR-22 users. Also, the chapter presents the results for the economics-related measures related to the price elasticity of demand and value-of-time calculation. Chapter 6 discusses the analysis of the toll transaction data and the results of the performance measures calculated for the PR-22 DTL and GTL. The last chapter contains the conclusions and recommendations gathered from the study results with suggestions for future investigations.

2. Research Methodology

This chapter explains the methodology followed in the study. The main intent of the study was to calculate performance measures to assess the effectiveness of the dynamic pricing mechanism employed in the PR-22 DTL facility and to estimate the willingness-to-pay (WTP) and assess the economic decision of PR-22 users of selecting the DTL facility. The methodology consisted of five major tasks, as shown in Figure 2.

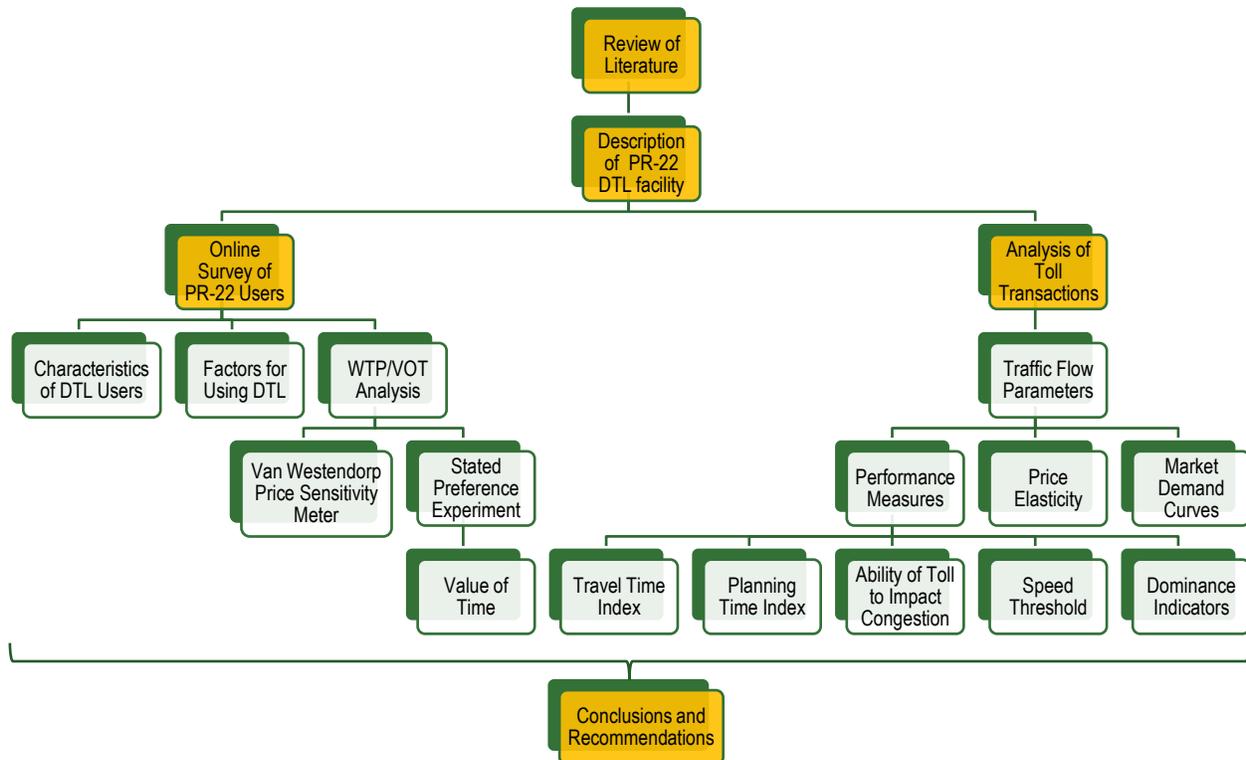


Figure 2 - Research methodology

The first task consisted of a comprehensive review of the literature on topics such as the implementation of managed lanes as a strategy for congestion mitigation on freeway corridors, a description of performance measures used to assess the effectiveness of managed lanes, a discussion about the type of goods, price elasticity, methods for calculating the WTP, and the calculation of the value-of-time (VOT). The main sources of information included reports from the Federal Highway Administration (FHWA) and the Bureau of Transportation Statistics, and technical articles from journals and conferences such as the Journal of Transportation Engineering of the American Society of Civil Engineers, the Journal of the Institute of Transportation Engineers, the International Journal of Transportation Engineering, and the Transportation Research Record of the Transportation Research Board, among others. Additional information and references were obtained from the monthly research meetings conducted with the TAMU team.

The second task was to characterize the prevailing conditions of freeway PR-22 along the DTL corridor. The DTL corridor is located from km-marker 22 in the Municipality of Toa Baja to km-marker 12 in the Municipality of Bayamón, directed towards the Municipality of San Juan. Physical and operational

characteristics of the facility were acquired from official reports and websites available from the Puerto Rico Highway and Transportation Authority (PR-HTA) – the freeway owner, Metropistas Puerto Rico – the freeway operator, and AutoExpreso – the toll system operator.

Two major data analysis activities were conducted for the study: an online survey of freeway users and the toll transaction data obtained for the PR-22 DTL corridor. These activities were performed in parallel, as depicted from the flowchart, with some of the analysis and results shared between tasks.

Access to the toll transaction database was authorized by the Puerto Rico Department of Transportation and Public Works (PR-DTPW). The database was provided by the AutoExpreso company. The 2019 database contained 186,731,549 transactions from the 13 GTL collection stations, and 2,049,537 transactions from the three DTL collection stations. The data files were divided by month and between the GTL and DTL transactions. Each data file included information related to each individual transaction recorded with transaction number, transaction date, transaction time, transponder number, vehicle class, toll paid, toll station location, travel direction, toll station name, and lane number.

The toll transaction data for the year 2019 were analyzed to calculate traffic flow parameters for freeway PR-22 along the DTL corridor. Vehicle counts per traffic direction, eastbound (EB) for the morning period and westbound (WB) for the afternoon period, for the GTL and the DTL were calculated for 5-minute periods each during the year. Separate vehicle counts were created for weekdays, weekends, and holidays. Individual vehicle speeds for the GTL and DTL were also calculated and averaged for 5-minute periods. Individual vehicle speeds were estimated using the time and distance between two successive toll collection stations. Speeds for the DTL traffic were calculated only for the EB direction. The vehicle speeds for the DTL traffic on the WB direction were not calculated due to the far-removed location of the second toll station and that the travel time estimated with that distance could be impacted by traffic conditions outside of the DTL. The toll paid was also averaged for every 5 minutes.

The traffic counts and the toll paid information were used to calculate seven performance measures to assess the effectiveness of the dynamic pricing mechanism in the PR-22 DTL facility. The selected measures were the Travel Time Index (TTI), the Travel Time Savings (TTS), the Planning Time Index (PTI), the Planning Time Index Benefits (PTIB), the Ability of Toll to Impact Congestion (ATIC), the Speed Threshold (ST), and the Dominance Indicators (DI). The ST is a speed-related measure established assessing the performance of high-occupancy vehicles (HOV) lanes. The ATIC measure is proposed in Burris et al. (2021). The DI is a new visualization measure proposed in this study based on the combined analysis of speeds and vehicle flow in the DTL and GTL.

A survey instrument was designed as part of the data analysis in this study. Given that the economic measures in the project scope require individual-based data, an online survey was developed to address these needs. The survey welcome message, in the Spanish language, which included a brief description and a map of the DTL on freeway PR-22 is shown in Appendix A. The online survey instrument was approved by the UPRM Institutional Research Board (IRB). The IRB authorization letter is included in Appendix B. Advertising efforts were made to acquire voluntary subjects for the survey that have the potential to be users of freeway PR-22 and the DTL. Ads were posted on Facebook social media focusing on residents and commuters of municipalities adjacent to freeway PR-22 from the San Juan Metropolitan Area and North-Central and Northwestern regions of Puerto Rico. Strict COVID-19 restrictions were established by the Government of Puerto Rico and the University of Puerto Rico at the time of the survey, therefore, interviews and other sampling methods, as well as official travel activities, requiring direct contact with participants were not available for the research team. Electronic messages inviting voluntary subjects were also sent by institutional email delivery service at the UPRM and the University of Puerto Rico at Río Piedras.

The sample size was estimated from an approximate population of 150,000 daily users of the PR-22 Buchanan toll station and an average of 5,627 DTL daily users, as estimated from the toll transaction data.

The survey received 522 responses from October and November 2020. After data cleaning, 518 unique responses were kept for analysis, representing an error margin of 4.3%.

The survey instrument had three sections titled: DTL Usage Factors, WTP Assessment, and Sociodemographic Factors. The questions were written in Spanish to facilitate receiving responses from residents. The survey included questions to identify users of the PR-22 DTL. A DTL user was defined as an individual that stated to have used the facility at least once. The DTL user restriction was not applied to the analysis of the WTP, the VOT, and the sociodemographic sections. A visual explanation of the subjects and survey sections is presented in Figure 3. The survey included 34 questions for stated DTL users and 27 questions for stated non-DTL users.

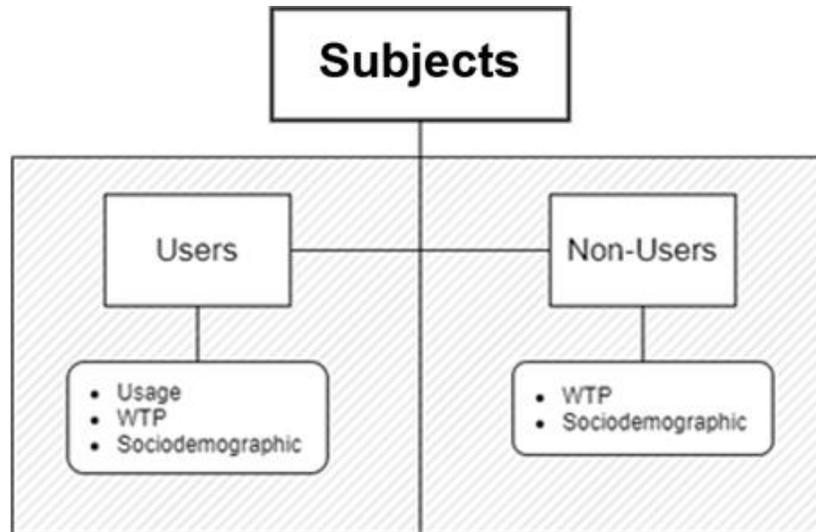


Figure 3 - Survey sections directed to DTL users and non-users

The DTL Usage Factors section had seven questions focused on collecting the stated DTL frequency of use and the DTL selection factors. Questions were included to determine the frequency of use for the periods before and after the COVID-19 pandemic was declared. Subjects were asked if their stated frequency of use of the DTL was related to the purpose of the trip (e.g., work, study, and leisure activities). The DTL selection factors were addressed using a Likert scale. The selection factors assessed were the toll price, the presence of traffic congestion in the GTL, travel time savings, trip urgency, climate conditions, and safety. Subjects were also asked about their perception of the reliability and time savings of the DTL.

The WTP Assessment section included four questions required to apply the Van Westendorp Price Sensitivity Meter (VWPSM) to estimate the WTP. These questions required respondents to directly type in price values. The VWPSM-related questions in the survey, translated to English, were:

- *At what price do you think the toll of the express lane is expensive, but are still willing to use it?*
- *At what price do you consider that the toll of the express lane is already too expensive to use it?*
- *At what price do you consider that the toll of the express lane is a "good buy" (bargain), and anyway would you use the lane?*
- *At what price do you think the toll of the express lane is so low that you would NOT use the lane?*

The stated preference experiment included nine questions in which the respondents were presented with combinations of three travel time savings (TTS) values and three DTL prices. The TTS values were 1, 7, and 15 minutes and the DTL price were \$1.00, \$4.00, and \$8.00. The TTS used for the scenarios were

based on extreme values and the average value of the actual distribution of travel time savings in the facility. The \$1 and \$4 prices relate to the minimum and maximum premium fees charged for using the DTL. The \$8 price is over the existing range of DTL prices and was included as a possible high premium fee for the use of the facility in the future. For each combination of TTS and toll price, each subject answered with a YES or NO response his/her willingness to use the DTL given the underlying conditions.

The Sociodemographic Factors section was used to gather standard sociodemographic information of the respondents, which in turn could be used for the proposed analyses. Among the sociodemographic variables asked were gender, age, income, education, and occupation.

The final task included the conclusions from the study from the perspective of the economic measures and the assessment of the PR-22 DTL pricing mechanism and included the comparative analysis with the performance results from the six freeway facilities analyzed by the TAMU team. The discussion also presents the recommendations for research studies and DTL improvement strategies to reduce congestion and increase the person-carrying capacity of the PR-22 corridor.

a. Dominance Indicators

Dominance Indicators (DI) are a new type of performance measure proposed in this study. The relative performance of different types of lanes within a highway facility can be analyzed using the multi-objective optimization concept of dominance¹. Assume that an operator seeks to maximize the average speed and vehicle throughput in the freeway lanes, (i.e., improving the performance of the lane types in terms of travel speed and vehicle throughput only). For a given period, the operation a lane type would dominate, or would be unequivocally better than another lane type, under two conditions:

1. If its average speed was greater than the average speed on the other lane types and if its vehicle flow was greater than or equal to the vehicle flow on the other lane types, or
2. if its vehicle flow is greater than the vehicle flow on the other lane types and if its average traffic speed is greater than or equal to the speed in the other lane types.

In other circumstances, both lane types would remain non-dominated. Based on this, a binary dominance indicator (D_b) could be defined by comparing the number of times that a lane type is better than another relative to the number of times that the opposite is true.

In the context of this study, D_b can be defined as follows. Let $\tilde{u}_{ML,t}$ and $\tilde{u}_{GTL,t}$ be the scaled average speeds at period t of the managed lanes (ML) and general-toll lanes (GTL), respectively, and let $\tilde{q}_{ML,t}$ and $\tilde{q}_{GTL,t}$ be the scaled flow at period t of the ML and GTL, respectively. The speeds could be scaled by a common maximum lane speed and the flows could be scaled by the respective lane type capacity. Additionally, define τ as the number of periods considered in the analysis. Then, the indicator can be computed as shown in Eq. 1:

$$D_b = \frac{\sum_{t=1}^{\tau} I_{ML,t}}{\sum_{t=1}^{\tau} I_{GTL,t}}, \quad (1)$$

where the binary variable $I_{ML,t}$ is defined as:

$$I_{ML,t} = \begin{cases} 1 & \text{if } \tilde{u}_{ML,t} > \tilde{u}_{GTL,t} \text{ and } \tilde{q}_{ML,t} \geq \tilde{q}_{GTL,t} \text{ or if } \tilde{u}_{ML,t} \geq \tilde{u}_{GTL,t} \text{ and } \tilde{q}_{ML,t} > \tilde{q}_{GTL,t} \\ 0 & \text{otherwise} \end{cases}$$

and $I_{GTL,t}$ is defined in a similar manner.

¹ A vector $\mathbf{f}(\mathbf{x}_1) = (f_1(\mathbf{x}_1), f_2(\mathbf{x}_1), \dots, f_k(\mathbf{x}_1))$ in the objective function space dominates another vector $\mathbf{f}(\mathbf{x}_2) = (f_1(\mathbf{x}_2), f_2(\mathbf{x}_2), \dots, f_k(\mathbf{x}_2))$ if $\mathbf{f}(\mathbf{x}_1)$ is better than $\mathbf{f}(\mathbf{x}_2)$ in at least one objective (i.e., coordinate) and it is not worse in all other objectives.

The relative performance of different lane types can also be measured based on the objective function space, as defined objectives of maximizing speed and flow, that is dominated by the operational states ($\tilde{u}_{it}, \tilde{q}_{it}$) of each lane type. Figure 4 illustrates this idea. The operational state ($\tilde{u}_{ML,t}, \tilde{q}_{ML,t}$) of the managed lanes dominates an area equal to $\tilde{u}_{ML,t} \times \tilde{q}_{ML,t}$ of the objective function space (i.e., all points in that area are dominated by the point $(\tilde{u}_{ML,t}, \tilde{q}_{ML,t})$), while the state of the GTL dominates an area of $\tilde{u}_{GTL,t} \times \tilde{q}_{GTL,t}$. In this example, the ML point happens to dominate the GTL point, but more informatively, note that, in general, the relative quality of their operations can be captured by computing the difference in the objective function space dominated by each lane type (i.e., $\tilde{u}_{ML,t} \times \tilde{q}_{ML,t} - \tilde{u}_{GTL,t} \times \tilde{q}_{GTL,t}$). Naturally, a negative difference means that the operation in the GTL outperforms the ML, while a positive difference communicates the opposite. The magnitude of the difference reveals the degree to which one lane type outperforms the other. The difference can be computed even when the operational states of each lane type are non-dominated.

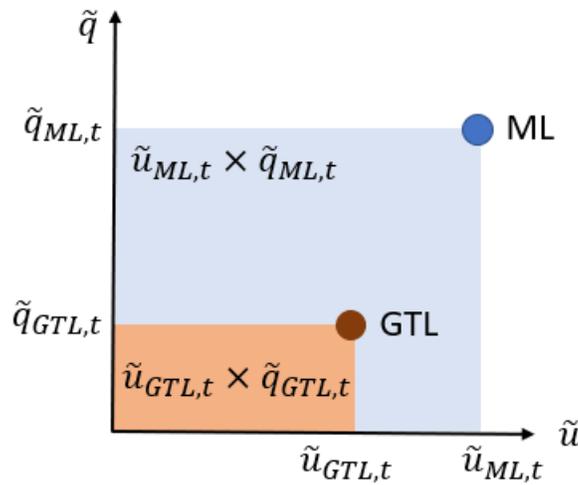


Figure 4 - Concept of objective space dominance

An aggregate measure of the relative objective space dominance (D_H) can be computed as shown in Eq. 2.

$$D_H = \frac{1}{\tau} \sum_{t=1}^{\tau} (\tilde{u}_{ML,t} \tilde{q}_{ML,t} - \tilde{u}_{GTL,t} \tilde{q}_{GTL,t}) \quad (2)$$

The D_H indicator is motivated by the hypervolume indicator commonly used in multi-objective optimization algorithms (Guerreiro et al., 2020). An attractive characteristic of the D_H indicator is that it can easily accommodate the consideration of additional performance objectives, as considered next. Let $\mathbf{p}_{ML,t}$ and $\mathbf{p}_{GTL,t}$ be vectors of performance operational states of the managed lanes (ML) and general-toll lanes (GTL), respectively, and h be the number of performance criteria considered. Then, D_H can more generally be defined as:

$$D_H = \frac{1}{\tau} \sum_{t=1}^{\tau} (\prod_{i=1}^c p_{ML,t,i} - \prod_{i=1}^c p_{GTL,t,i}) \quad (3)$$

In the case considered in Eq. 2, $c = 2$, $p_{ML,t,1} = \tilde{u}_{ML,t}$, $p_{ML,t,2} = \tilde{q}_{ML,t}$, and $\mathbf{p}_{ML,t} = (\tilde{u}_{ML,t}, \tilde{q}_{ML,t})$; similar expressions can also be defined for the GTL. The value of D_H is bounded between -1 and 1, although in practice it is unlikely that values in these bounds would be observed.

The Speed Threshold-based Dominance (D_S) indicator is proposed for agencies that are interested in considering the performance of lane types based on their vehicle throughput and traffic speeds and a

given speed threshold u^* above which the lanes are considered to have an acceptable operation. First, let u_{it} be the unscaled traffic speed on lane type i , at period t , and define the performance measure s_{it} as:

$$s_{it} = \begin{cases} \tilde{u}_{it} \tilde{q}_{it} & \text{if } u_{it} \geq u^* \\ \tilde{u}_{it} \tilde{q}_{it} - 1 & \text{if } u_{it} < u^* \end{cases} \quad (4)$$

The s_{it} measure is bounded between -1 and 1; taking a value of -1 when there is no flow and traffic speed is zero and a value of 1 in the unlikely scenario that both the scaled traffic speed and flow are equal to one. This variable is positive when the traffic speed on the lanes is greater than the threshold, and negative when the opposite is true. Note that the s_{it} measure shares terms found in the D_H indicator, obviously with modifications to include the u^* consideration. The D_S indicator captures the average gap between the s_{it} measures of the lane types. In the context of this project, the indicator can be defined as:

$$D_S = \frac{1}{\tau} \sum_{t=1}^{\tau} (s_{ML,t} - s_{GTL,t}) \quad (5)$$

The indicator D_H is bounded between -2 and 2, with positive values indicating that the managed lanes outperform the GTL and negative values indicating the opposite.

3. Literature Review

This chapter presents a comprehensive review of literature about the types, benefits, and performance evaluation of managed lanes. The chapter also explains in detail each of the performance measures selected to assess the effectiveness of managed lane operations, and a discussion of topics related to market demand curves, price elasticity of demand, and methods to estimate the WTP of road users.

a. Types and Benefits of Managed Lanes

Traffic congestion in the highway network in the U.S. and Puerto Rico is constantly growing. The search for effective and innovative congestion management alternatives is constantly ongoing by transportation agencies and road managers. The incorporation of managed lanes (ML) as an innovative strategy to manage traffic congestion on a roadway has been promoted in lieu of recommending the expansion of the physical capacity of the highway network. Managed lanes are defined by Caltrans [2021] as *“an operational practice utilized to address congestion by controlling traffic movement on the highway.”* Likewise, the Texas DOT defines it as a facility that increases freeway efficiency by packaging various operational and design actions [Kuhn et al., 2005]. There are approximately more than 70 managed lane facilities in operation in the U.S., while other 34 are being designed or under construction [TRB Managed Lanes Committee, 2021]. California, Texas, and Florida are the states with the largest number of facilities in the U.S. About 40% of the total network of managed lanes in the U.S. are in California, primarily around the urban areas of Sacramento, San Francisco, Los Angeles, and San Diego. Data from over 40 years demonstrate that the strategy has achieved the benefits and desired performance levels in at least 28 metropolitan areas in the U.S., Canada, Australia, and Europe [FHWA, 2011].

Most of the earliest permanent managed lanes implemented in the U.S. were applications of bus or HOV lanes, motivated as a response to the oil crisis during the 1970's [NASEM, 2016; Turnbull, 2003]. The first permanent implementation of managed lanes was established in 1969 with an exclusive busway on the Shirley Highway in Virginia [FHWA, 2008a]. This facility was conceptualized in 1964 as the main road link between Washington D.C. and Richmond, Virginia. The facility added a carpooling/ridesharing policy in 1975 allowing HOVs to enter the busway lanes. The final state of the project provided a facility with two reversible express lanes and three general-purpose lanes in the peak travel direction [Kozel, 2002].

The evolution of managed lanes has provided additional active traffic and lane management strategies, as depicted in Figure 5. There are different types of facilities based on their access control, vehicle eligibility, and pricing conditions. A managed lane can implement a combination of these conditions considering the level of complexity required for its operations.

The vehicle eligibility condition has been a common characteristic used for managed lanes for the past 40 years. This condition refers to the application of lane use restrictions by type of vehicle or vehicle occupancy [Kuhn et al., 2005]. Examples of vehicle restrictions could include access only for motor vehicles with multiple occupants (i.e., HOVs), or for transit buses or trucks, among others.

The selection of the vehicle eligibility criteria is analyzed with respect to the anticipated utilization of the facility and the benefits from its use by the vehicle type allowed or desired occupancy. The major goal is to promote the usage of the facility by vehicles with higher occupancy, instead of focusing on moving more vehicles, and reduce the congestion impact on the environment. Two examples for this application are HOV and truck lanes to ensure easier mobility of the traffic demand. The vehicle restriction can consider meeting specific standards or goals of number of people per vehicle, travel time savings, average speeds, level of service for transit services, or air quality impacts. Vehicle eligibility restrictions can also be established by the time of day, such as allowing or excluding the use of the managed lanes for specific

vehicle types during the peak periods or off-peak periods to control the average usage of the lanes. An example of this application is located on the I-10 Katy Freeway in Texas with a one-lane reversible facility that allowed HOVs on Mondays through Fridays from 6 to 11 a.m. in the inbound direction and from 2 to 8 p.m. in the outbound direction [Avelar and Fitzpatrick, 2018]. This strategy provided that the managed lanes improved reliable travel times for the transit buses and carpoolers.

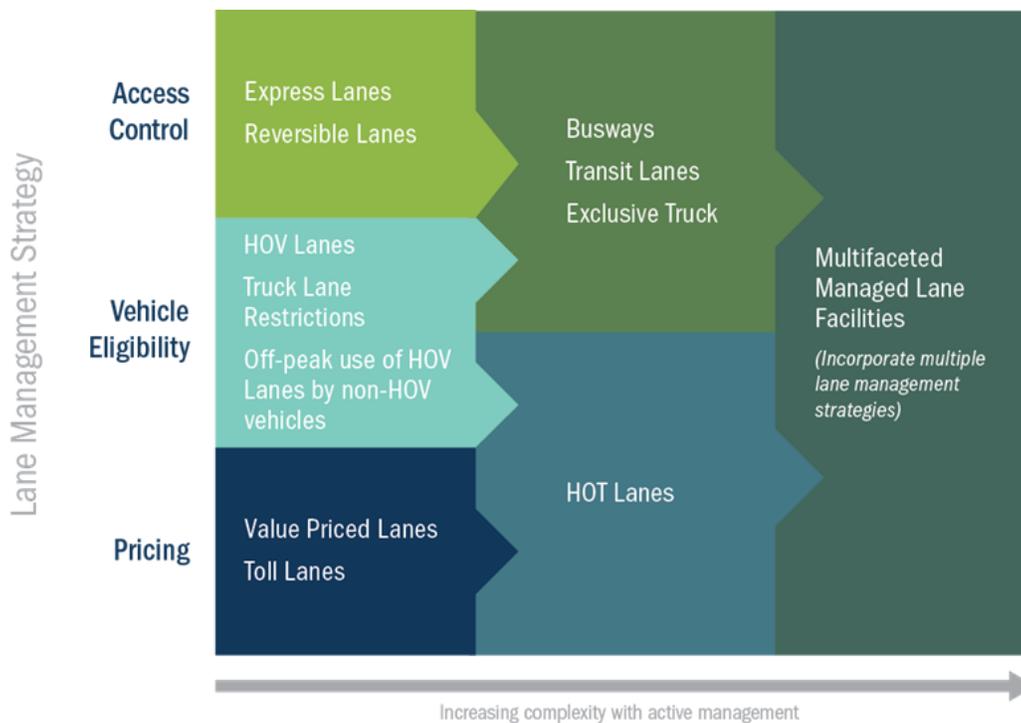


Figure 5 - Lane management strategies and complexity
(Source: Texas Department of Transportation)

The second condition is access control. This condition has been applied in various facilities, but generally is implemented in combination with other conditions. Examples are express lanes and reversible lanes. Express lanes increase roadway capacity by providing users with the alternative of an additional lane. These lanes help to reduce delays, manage congestion, and keep travel times reliable for travelers. Meanwhile, reversible lanes add peak-direction capacity to a two-way road and decrease congestion by using the available lane capacity from the unused lanes in the off-peak direction. The application of these conditions depends on the location, agency practices, frequency of re-analysis, supporting policies or actions needed, and other complementary strategies. Figure 6 shows an example of a roadway section with a one-lane reversible barrier-separated lanes along the median. The DTL on PR-22 incorporates two barrier-separated reversible lanes along with its median that also serve as a busway facility.

The pricing strategy is the third condition. The price for the use of the facility can be established based on the vehicle occupancy, speed, and counts or congestion-related measures, and could also require registration to users. The pricing mechanism is either established with a fixed or variable quantity that is managed electronically. To control the quality of the service in the managed lanes, the toll rate could increase during peak periods when the traffic demand is higher. The variable toll rates can be set either with static or dynamic toll values. The static pricing establishes the variable toll using a predetermined value based on the time of day, a toll-table, or a schedule for the vehicle types. On the other hand, the dynamic pricing adjusts the toll based on the prevailing traffic conditions, such as density, speeds, or

departure time, on the corridor. Setting the dynamic pricing relies on an algorithm. Two types of toll algorithms are common: discrete and continuous algorithms. A discrete algorithm uses predetermined tables that output price changes for pre-defined traffic changes or volumes. A continuous toll algorithm establishes the toll rate using real-time traffic conditions. The dynamic toll algorithms consider traffic parameters in the managed lane only or using a combination of performance metrics for the managed and general-purpose lanes.

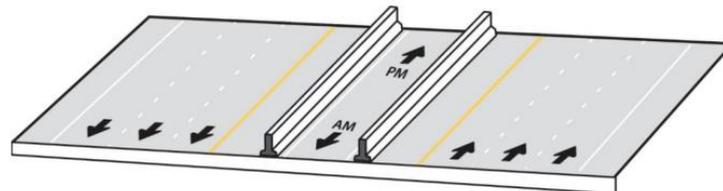


Figure 6 - Typical freeway cross-section with reversible managed lanes
(Source: NASEM, 2016)

The most used strategies for managed lanes are [FHWA, 2011]:

1. High-Occupancy Vehicle (HOV) Lanes: The use of these lanes is restricted by the vehicle occupancy. A minimum of two or more persons inside the vehicle is typically required to be eligible. This strategy is implemented generally to promote carpooling and reduce pollution.
2. High-Occupancy Toll (HOT) Lanes: Practically the same concept of HOV lanes, but with a tolling strategy. The toll is charged to those users that do not meet vehicle occupancy requirements of the facility. Vehicles with two or more-person vehicles can be charged with a lower or no fee, in comparison to single-occupancy vehicles.
3. Dynamic Shoulder Lanes: The use of a shoulder as a designated travel lane could be implemented when congested traffic levels occur during the peak periods of traffic on the corridor. The strategy could be implemented as a temporary designation because of road crashes or other special conditions. It is continuously monitored using real-time conditions and is opened or used only in the specified conditions.
4. Dynamic Toll Lanes (DTL): This strategy ensures traffic flow quality in the managed lanes by implementing a dynamic toll strategy that adjusts its price according to existing traffic conditions. The implementation requires the combination of sensors to collect real-time traffic information, video technology to identify roadway crashes or traffic incidents, and communication with drivers through variable message roadway signs.
5. Truck Lanes: Lanes designated for truck-only use. Their application is commonly used for corridors with a significant percentage of commercial trucks of large size and weight (e.g., 80,000 pounds of Gross Vehicle Weight and lengths exceeding 75 feet). This type of facility improves safety due to the separation of heavy vehicles from the traffic on the GPL, that due to their larger size and weight, lower braking reaction, and need for maintaining constant speeds can increase the likelihood of crashes.

The benefits of the implementation of managed lanes include the encouragement of ridesharing (carpool), the optimization of the person-carrying capacity of the highway, and travel time reduction. Although the focus of the strategy is usually directed toward improving the quality and efficiency of the freeway operations, such as the reduction of congestion, optimized vehicle throughput, better predictable travel times or improved trip reliability, and higher vehicle speeds, there are other benefits associated with managed lanes. These include the support of transit usage, provide travel choices to commuters,

reduction in fuel consumption, and reduced vehicle emissions that positively influence the air quality [FDOT, 2021].

Managed lanes are not the panacea for congestion reduction that can be implemented anywhere and under any condition. The implementation of each strategy must be analyzed thoroughly, and the existing constraints and potential impacts must be evaluated. There are, naturally, critics of this strategy that oppose their construction or implementation. For example, critics of HOT lanes argue that the strategy is not a long-term solution to congestion, that it is detrimental to carpools, that they have social equity problems, and that they ultimately waste public funds that could have been invested in less auto-centric strategies [Posey, 2016]. Other critical issues to be considered in the implementation of the strategy include the adverse impact on traffic on the GPL, cost-effectiveness implications, public acceptance, legal implications, and the environmental impact [Kuhn et al., 2005].

b. Performance Measures

FHWA refers to performance measurement as: “...a process of assessing progress toward achieving predetermined goals, including information on the efficiency with which resources are transformed into goods and services, the quality of those outputs and outcomes, and the effectiveness of government operations on terms of their specific contributions to program objectives” [Neudorff et al., 2006]. Performance measurement uses empirical evidence to determine the progress toward a specific facility objective or the expected impact on the system [FHWA, 2008a]. As performance measures are relative to the goals or objectives that the roadway facility is intended to meet; a variety of applications are recommended to assess the ability and extent of achieving goals related to mobility or congestion mitigation, reliability, safety, accessibility, economic development, quality of life, environmental and resource consumption, system preservation, and system and organizational efficiency goals [Carson, 2005; Neudorff et al., 2006]. performance measures rely on the compilation of basic traffic flow characteristics of the facility like vehicle speeds, traffic volumes, traffic density, and can be vehicle or period specific. Since a common goal is to reduce congestion in a freeway segment, the focus usually goes to evaluate the quantity and quality of traffic flow, vehicle throughput, travel times and delays, and the reliability of the operations. Highway agencies and DOTs establish targets or threshold values for the selected measures, the data collection procedures, and the evaluation and monitoring techniques to develop the performance assessment of the managed lanes. A general description of the performance measures used in this study to assess the PR-22 DTL facility follows.

i. Travel Time Index

The Travel Time Index (TTI) is defined as the ratio of travel conditions in the peak period to a target or acceptable (i.e., free flow) travel condition [Neudorff et al., 2006]. TTI explains how much longer a trip will take during the peak period and is calculated as shown in Equation 6.

$$TTI = \frac{\text{peak period travel time}}{\text{free-flow travel time}} \quad (6)$$

The TTI value estimated for the SJMA for the year 2017 was 1.33, which represents that a trip of 15 minutes on free-flow conditions will take 20 minutes during the peak period of traffic. The TTI for the SJMA for the year 2017 is the 15th highest value for U.S. urban areas [Schrank et al., 2019].

ii. Travel Time Savings

The Travel Time Savings (TTS) is the difference between the travel times for different lane types in the freeway segment, (i.e., DTL vs. GTL), or different periods, (i.e., peak vs. off-peak). For this study, the TTS represents the saved time by the freeway user when choosing the DTL over the GTL. The analysis of the TTS can add valuation using standardized cost-per-hour-per-person figures for different vehicles. The TTS, in minutes, is calculated as shown in Eq. 7:

$$TTS = TT_{GTL} - TT_{DTL} \quad (7)$$

where:

TT_{GTL} = travel time on the general toll lanes, in minutes

TT_{DTL} = travel time on the dynamic toll lanes, in minutes

iii. Planning Time Index

The Planning Time Index (PTI) is a reliability travel time measure that explains how much time the user needs to plan to travel in and out of the facility during the peak hour period to avoid being late [Schrank et al., 2019]. The PTI is calculated as the ratio of the 95th percentile peak period travel time to the free-flow travel time in the facility, as shown in Equation 8.

$$PTI = \frac{95th \text{ percentile travel time}}{Free-flow travel time} \quad (8)$$

The PTI value estimated for the SJMA for the year 2017 was 2.50. A PTI of 2.5 represents that a commuter must plan for 37.5 minutes during the peak period when making a trip that takes 15 minutes during free flow to avoid being late at least one time in a month. The PTI for the SJMA for the year 2017 is the 4th highest value for U.S. urban areas [Schrank et al., 2019].

iv. Planning Time Index Benefit

The Planning Time Index Benefit (PTIB) is a measure of the difference between the PTI values calculated for the GTL and the DTL. The PTIB is calculated as shown in Equation 9.

$$PTIB = PTI_{GTL} - PTI_{DTL} \quad (9)$$

where:

PTI_{GTL} = Planning Time Index on the general toll lanes

PTI_{DTL} = Planning Time Index on the dynamic toll lanes

v. Ability of Toll to Impact Congestion

The Availability of Toll to Impact Congestion (ATIC) is a measure that explains mathematically the effect of how the congestion is being balanced by the toll price in the managed lanes [Burris et al., 2021]. ATIC is defined as the percent change in the traffic flow divided by the percent change in toll price in a period (see Eq. 10).

$$ATIC = \frac{\% \text{ change in average vehicle throughput in the managed lanes}}{\% \text{ increase in toll}} \quad (10)$$

vi. Speed Threshold

The Speed Threshold (ST) is a measure based on the average vehicle speeds in the facility. This measure is established as a standard for HOV facilities in the USC Title 23 Highways Chapter 1 Federal-Aid Highways Section 166 HOV Facilities (d)(2)(A) that indicates that “...the operation of a HOV facility shall be considered to be degraded if vehicles operating on the facility are failing to maintain a minimum average operating speed 90 percent of the time over a consecutive 180-day period during morning or evening weekday peak hour periods (or both)” [FHWA, 2016]. The minimum average operating speed is defined as:

1. 45 mph, in the case of a HOV facility with a speed limit of 50 mph or greater; and
2. not more than 10 mph below the speed limit, in the case of a HOV facility with a speed limit of less than 50 mph.

c. Demand Curves and Elasticity

Demand curves can be represented in Economics as the optimal interaction between price and quantity demanded of a good or service [Varian, 2015]. Express toll lane usage, as all goods and services, can be modeled using demand models. As per the Economics: Pricing, Demand, and Economic Efficiency [FHWA, 2008b], demand curves can be depicted as the relationship between travel cost of demand and cost of travel. Given this relationship, the cost of travel is determined as the price of access to the express toll lane, and quantity demanded as traffic volume. Janson and Levinson [2014] represent the quantity demanded as vehicular density and managed lane share percentage. According to the general law of demand with all other things being equal (i.e., *ceteris paribus*), there is an inverse relationship between price and quantity demanded, thus if the price of a good or service increases, its quantity demanded decreases, and vice-versa [Jensen and Miller, 2018; McConnell, 2019]. However, there are certain goods that seem to behave in patterns that contradict said law. Veblen and Giffen goods seem to deviate from this behavior as an increase in price exacerbates the amount of quantity demanded [Abulibdeh and Zaidaya, 2018]. Veblen goods are limited to super-luxury items such as rare artworks, collectible items, and high-end dishes, among others. Demand for these goods is tied to the perception that the consumers have of them; that is, if the consumer believes that the price reflects “attainability”, it will consume less of the good, and vice versa. Alternatively, Giffen goods are even odder, with some academics considering them to be purely theoretical, except for rare and punctual cases such as the one described by Jensen and Miller [2008], in which rice and wheat exhibited Giffen behavior in two distinct Chinese provinces.

The demand for priced managed lanes appears to behave contrary to the demand of normal goods (whose demand shows a direct relationship with the consumer’s income). Considering a dynamic toll price scheme, Janson and Levinson [2014] point to an increase of vehicular density in the time intervals where the price level was increasing. Such behavior may very well point to a violation of the law of demand. Yet, user perception of a price increase seems to be directly related to a perception of possible worsening traffic flow conditions in the general-purpose lanes at or farther in the user’s trip, and higher travel time savings for the use of the DTL. This perception may, for some users, provide greater utility and increase consumption of the DTL even though its price increases. This apparent exception to the law of demand can be explained as the user’s perception of the DTL becoming a different good that provides higher utility due to the reduced travel time, causing its demand curve to shift to the right, rather than having a positive slope. Before using the DTL, the driver may assess their willingness-to-pay (WTP) for the toll by comparing two different goods with different time savings [Janson and Levinson, 2014].

It is of great interest to measure the DTL demand’s responsiveness to changes in toll price. Failure in the pricing algorithm to efficiently control demand in the DTL could create externalities such as traffic congestion. The price elasticity of demand (ϵ) is defined as the percentage change in quantity demanded

divided by the percentage change in price [Varian, 2015]. Several methodologies have been suggested to calculate the price elasticity of demand. For this study, a log-log regression model was used, consisting of the logarithmic transformation of the variables, price and quantity demanded, and a subsequent ordinary least squares (OLS) regression of the transformed variables. An advantage of this model is that the estimated model coefficient for each independent variable is the elasticity of the dependent variable with respect to the independent variable. Thus, if a 1% increase in price P occurs, a $\pm\epsilon\%$ increase/decrease in the quantity demanded Q can be expected [Varian, 2015; Gujarati, 2009]. The model of the price elasticity of demand is presented in Equation 11 as:

$$\ln(Q_i) = \beta_0 + \beta_1 \ln(P_i) + e$$

$$\epsilon = \beta_1 = \frac{\partial \ln(Q)}{\partial \ln(P)} = \frac{\partial Q/Q}{\partial P/P} = \frac{\partial Q}{\partial P} \cdot \frac{P}{Q} \quad (11)$$

Studies have pointed to inelastic values of different managed lanes throughout the U.S. Janson and Levinson [2014] report elasticity values ranging from 0.03 to 0.85 for the MnPASS HOT lanes, while Liu et al. [2011] report values of 0.21 to 0.60 in the SR91 California HOT lanes. This behavior has also been related to the positive relationship between price and quantity demanded, as reported by Abulibdeh et al. [2018] and Janson and Levinson [2014]. Meanwhile, Burriss and Pendyala [2002] and Odeck and Bråthen [2008] report negative inelastic elasticity of drivers in toll bridges in Florida and toll roads in Norway. Furthermore, elasticity values of -0.16 and -0.21 have also been reported for the SR167 HOT Lanes in Washington State [Brent and Gross, 2017].

Gardner et al. [2013] modeled the choice process of drivers that use a HOT lane using the I-394 corridor in Minnesota. The traffic on the managed lanes is monitored continuously, and the toll price is adjusted every 3 minutes based on the traffic congestion. To understand the decision behavior of the freeway users, a toll algorithm was compared using a constant toll rate value with a time-varying toll. The algorithm was done using formulas that included the travel time on the HOT lanes, the lane choice probability, the flow coming with upstream and downstream counts, and time increment. The study found that the variation of the lane choice decision depends on the vehicle class, demographic factors, trip purposes, and individual heterogeneity.

d. Willingness-to-Pay

Price is one of the most contributory factors that affect the consumer's preferences when consuming a good or service. Consumers have also added importance to an array of factors such as quality, promotion, and distribution channel [Ceylana et al., 2014]. The willingness-to-pay (WTP) can be broadly defined as the price range, maximum or minimum, that a consumer would pay to buy or obtain a good or service. The maximum price which the individual is willing to pay, also called the reservation price, reflects the consumer's indifference in the decision to consume or not the good [Kloss and Kunter, 2016]. Thus, if the price is higher than the reservation price, the consumer may opt to not consume the good or service, since its consumption no longer provides utility. Understanding the consumer's WTP is crucial to determine the efficiency and functionality of pricing strategies of a good. Several techniques have been developed to assess the consumers' WTP, including direct and indirect methodologies [Kloss and Kunter, 2016]. Direct methodologies include techniques that directly ask the consumer for a price or range of prices in which the individual is willing to pay, or not, for a good or service. This direct questioning may be in the form of contingent valuation, in which the researcher may ask the subject, "*what is the maximum price you would be willing to pay to buy X product?*" Contingent valuation methods have been widely utilized in marketing and pricing research to determine the WTP of consumers, as they employ direct

questions about specific prices and price points to consumers [Kloss and Kunter, 2016]. One of the main weaknesses of contingent valuation techniques is the hypothetical nature of the test subject's response. Given that the answers that the consumers provide are of non-committal nature and only reflects their WTP, they do not necessarily reflect the real intention of consumption, for which the external validity of these techniques has been disputed [Wertenbroch and Skiera, 2002].

The literature also points to the use of the Becker-DeGroot-Marshack (BDM) technique by Becker et al. [1964] as a precursor mechanism to calculate the WTP [Kloss and Kunter, 2016]. The BDM method, as illustrated by Keller et al. [1993], points to the use of economic incentives for decision-makers to reveal their true nature of the subjective value of goods and services. The method's design has been modified through the years by researchers to employ the use of lottery and auction-style experiments. Given the nature and population of this study, the BDM method is not suitable. Furthermore, the utilization of single price points determination techniques, may not correctly represent the value-based pricing factors employed by consumers when evaluating their WTP for goods or services.

e. Van Westendorp Price Sensitivity Meter

The Van Westendorp Price Sensitivity Meter (VWPSM) provides a value-based approach for the determination of the consumer's WTP. The main assumption of the VWPSM is that consumers cannot express a single "perfect price" for a good or service, yet a range of prices is based on the perceptions of quality and price. Thus, the method addresses how the perceptions of the value of the consumer are influenced by the price and quality factors [Ceylana et al., 2014]. The VWPSM design consists of the utilization of four price-specific questions which are termed as "too cheap", "cheap", "expensive", and "too expensive." These questions present different specifications in which the consumer is asked about the price at which it perceives aspects of quality and price perception:

1. "Too cheap": the price of the good is so low that the consumer will not utilize it.
2. "Cheap": the price of the good provides a "great value for the money" or is considered a bargain.
3. "Expensive": the price of the good is expensive, but still the consumer utilizes it.
4. "Too expensive": the price of the good is so high that the consumer does not utilize it.

The responses from the test subjects are then plotted in cumulative percentage curves for each of the four questions, as shown in Figure 7. Utilizing said curves, the following four intersection points between the curves can be obtained [Kloss and Kunter, 2016]:

1. Point of Marginal Cheapness (PMC): Price point at which the same proportions of respondents perceive the good/service as "not cheap" and "too cheap." Prices under this point would reflect lesser consumption due to consumers' concerns about quality, exceeding the increase in consumption from "bargain hunters."
2. Point of Marginal Expensiveness (PME): Price point at which the same proportions of respondents perceive the good/service as "not expensive" and "too expensive." Prices beyond this point could reflect that the good/service is too expensive for the value derived from it.
3. Optimum Price Point (OPP): Price point at which the same proportions of respondents perceive the good/service as "too expensive" and "too cheap." Prices at this point represent minimal resistance from the consumers to the price.
4. Indifference Price Point (IPP): Price point at which proportions of consumers feel the good/service is "cheap" and "expensive." Prices at this point are indifferent to most consumers.

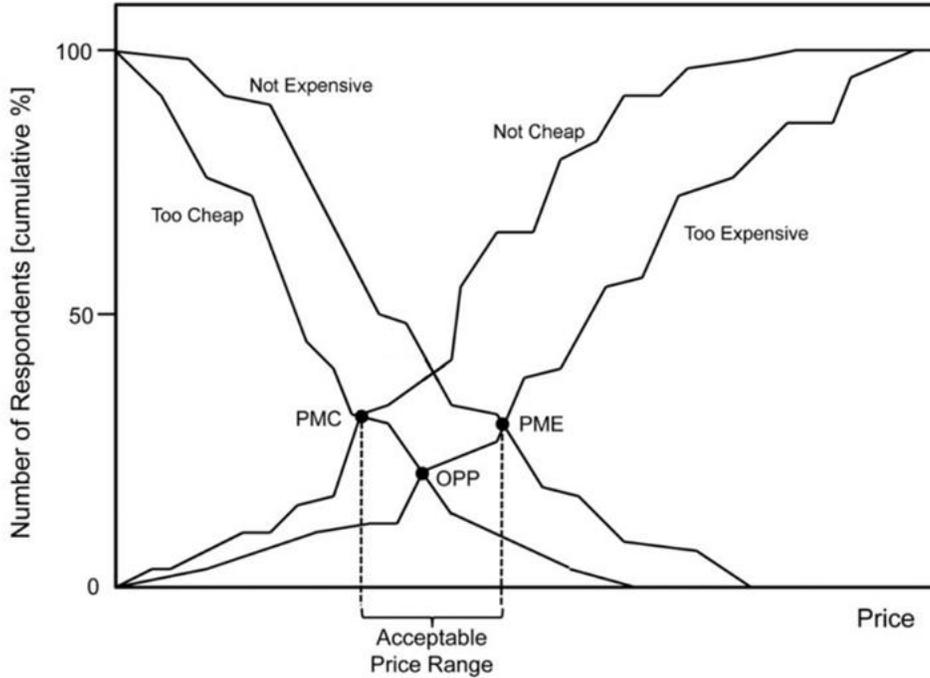


Figure 7 - Van Westendorp Price Sensitivity Meter
(Source: Kloss and Kunter [2016])

The price points are useful in the determination of the Acceptable Price Range as the PMC and the PME set the boundaries of this range [Ceylana et al., 2014]. Ceylana et al. [2014] define the IPP as the price of the good/service offered by a market leader. In our study, due to the lack of any substitutes and any local market in DTL, the authors do not believe that an interpretation of IPP values can be applied.

f. Discrete Choice Analysis

Discrete choice analyses are indirect tools to obtain WTP values from stated preference surveys [Kloss and Kunter, 2016]. Discrete choice models have been a popular alternative to analyze and predict an individual's choice of one alternative from a set of presented mutually exclusive and collectively exhaustive alternatives [Koppelman and Bhat, 2006]. Thus, it is of great interest to predict the behavior of a group of individuals based on the influence of different attributes in the decision-making process. Disaggregate discrete choice allows modeling of an individual choice response as a function of alternatives available and the sociodemographic characteristics of the individual [Koppelman and Bhat, 2006]. These models align themselves with utility-based choice theory. Individuals will always look to maximize their utility, indicator of value, hence they will select the alternative that maximizes their utility [McConnell, 2019; Varian, 2009; Koppelman and Bhat, 2006]. This model can be expressed mathematically as follows:

$$U(A_i, S_h) \geq U(A_j, S_h) \Rightarrow i > j \quad \forall j \in P \quad (12)$$

where:

$U()$ = the utility function

$A_{i,j}$ = vector attribute of the alternative i,j

S_h = vector of the characteristics of individual h

$>$ points to preference of one alternative over the other, and

\forall points to instances of the condition for all the cases of the alternative.

An interpretation to the mathematical expression in Eq. 12 can be described as: if the utility of alternative i is greater or equal than the utility of alternative j , then alternative i is preferred to alternative j for all the cases of j in a pool of alternatives P . As observed in the expression, these utilities have underlying attributes A of the alternatives related to the model and characteristics S related to the individual [Koppelman and Bhat, 2006].

Discrete choice studies have attempted to model transportation utilities based on travel costs and fuel prices. Abhir et al. [2017] modeled utility curves based on travel time and time reliability of the managed lanes from the Katy Freeway in Texas with traffic and toll data to calculate the Value of Time (VOT) and the Value of Reliability (VOR). Values for the VOT on managed lanes have been calculated and reported. Small et al. [2005] calculated a VOT of \$21.46 for a variable toll rate mechanism in the SR91 route in Los Angeles, California. Burriss et al. [2012] calculated the VOT for the Minnesota I-394, which yielded a morning VOT of \$73/hr and \$116/hr in the afternoon. Janson and Levinson [2014] found VOT values for the same facilities ranging from \$60/hr to \$124/hr. Concas and Kolpakov [2009] provide an extensive summary of previous research related to VOT and VOR.

4. Description of the Freeway PR-22 DTL

This chapter provides a general description of the physical and operational characteristics of the dynamic toll lanes (DTL) of freeway PR-22. In addition, basic traffic flow statistics and toll transaction data for the DTL from the year 2019 are provided.

Freeway PR-22, also known as the José de Diego Expressway, is an access-controlled toll highway with a length of 52.5 miles on the North region of Puerto Rico, extending from the Municipality of Hatillo to the Municipality of San Juan. Figure 8 shows the extension of freeway PR-22 with the location of the toll collection stations and the DTL corridor. PR-22 is part of the U.S. Interstate Highway System as an unsigned component of Interstate PR-2. The construction of PR-22 started in 1971 and is currently the most heavily traveled highway in the territory. Annual Average Daily Traffic (AADT) values of 218,501 vpd and 208,721 vpd were registered in the year 2012 to the east of the Buchanan station at kilometer markers 0.70 and 5.40, respectively [PR-HTA, n.d.]. The basic typical cross-section of the freeway includes two lanes and two shoulders per direction separated by a grass or paved median to the west of the Vega Alta Toll Station. The typical cross section to the east of the Vega Alta Toll Station increases to six, eight, nine, and eleven total lanes as the corridor goes east and reaches the SJMA. The speed limit of the facility is posted at 65 mph to the west of the Toa Baja Toll Station and 55 mph to the east of the Toa Baja Toll Station. PR-22 has 13 toll collection stations, with six stations EB and seven stations WB. The DTL has three additional toll collecting stations at the entry points (two EB and one WB).



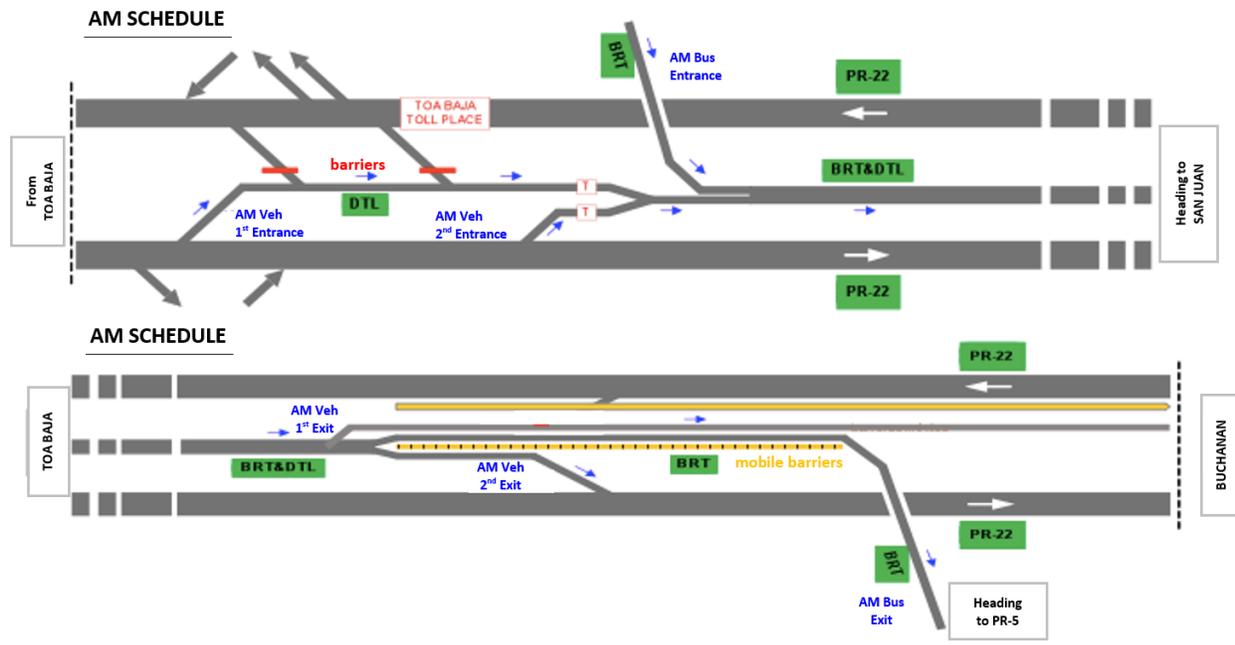
Figure 8 - Location of toll stations and DTL corridor in freeway PR-22

(Source: Metropistas, 2016)

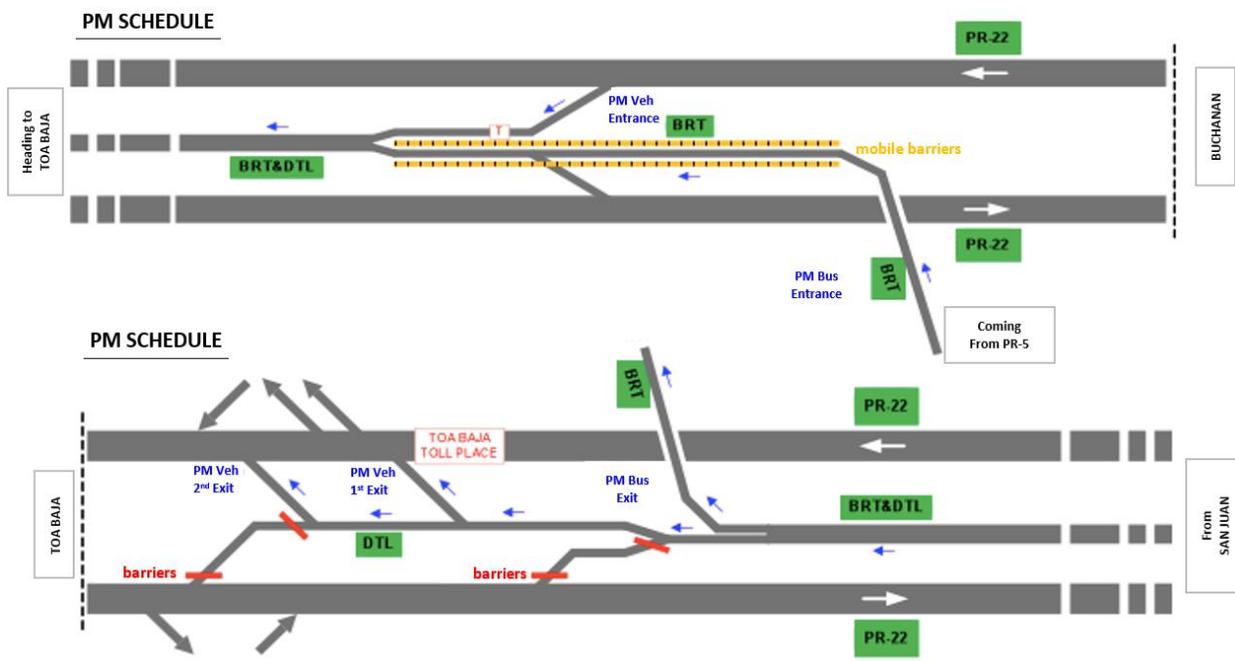
Freeway PR-22 was designated as a public-private partnership (PPP) project with a private operator responsible for the operations, maintenance, and reconstruction activities of the freeway. The PPP concession included freeway PR-5. The PPP contract with Autopistas Metropolitanas de Puerto Rico, LLC (Metropistas), an Abertis Infraestructuras company, as the selected operator for the two freeway corridors was approved in June 2011 with a contracting term of 50 years.

a. Characteristics of the PR-22 DTL corridor

The DTL facility opened in August 2013 and has a length of 12 km (7.7 mi) between the Toa Baja and Buchanan toll stations. The DTL corridor provides two lanes along the median of PR-22, in a reversible operation going EB toward San Juan in the morning and WB out of San Juan in the afternoon. The speed limit in the DTL is 45 mph. A 40-mph speed limit is posted along a short segment at the start of the facility in the western extreme of the corridor. Figure 9 shows the entry and exit points and the reversible operational scheme of the DTL corridor.



(a) AM Operation



(b) PM Operation

Figure 9 - PR-22 DTL entry and exit points and operational scheme
(Modified from: Metropistas, 2020)

The DTL going EB has two entry points, one before and one after the PR-165 ramps, and two exit points, one before and one after the PR-5 ramps. In the WB direction, the DTL has one entry point before the PR-167 ramp and two exit points, one after and one before the PR-165 ramps. The toll is collected at the entry points in both directions. Stations 112 and 113 correspond to the EB entry points. Station 111

corresponds to the WB entry point. The operation is from 4 a.m. to 12 p.m. going EB and from 12 p.m. to 4 a.m. going WB. The median lanes also function as a busway for the “Metro Urbano” express bus service that operates from 6 a.m. to 7 p.m.

b. Toll Pricing Scheme

PR-22 has 16 toll collection stations: 13 stations for the GTL and three stations for the DTL. The Factor Toll Station is the only station located on an entry ramp. All the other twelve toll collection stations for the GTL work as bidirectional pairs. The tolls charged to the users of the GTL have fixed values for seven different vehicle classes. Figure 10 presents the vehicle classification used for PR-22.

Vehicle classes		
		
Class 1 Motorcycles and 2-axle cars up to 76 inches wide	Class 2 Other 2-axle vehicles	Class 3-7 3- to 7-axle heavy duty and tow-truck vehicles

Figure 10 - Vehicle classification for toll pricing scheme

(Modified from: <https://metropistas.com/mapas-y-tarifas/>)

Tables 1 and 2 show the location and description of the toll rates charged per vehicle class at each of the GTL stations for the EB and WB directions, respectively. The lowest toll charged is \$0.70 for a vehicle class 1 at nine GTL stations. The highest toll charged corresponds to class 7 vehicles with a rate of \$3.60 at four GTL stations.

Table 1 - PR-22 toll pricing scheme for the EB direction

Plaza ID	Plaza Name	Toll Price per Class						
		1	2	3	4	5	6	7
1	Hatillo	\$0.70	\$1.35	\$1.70	\$2.00	\$2.30	\$2.65	\$2.95
2	Arecibo	\$1.00	\$2.00	\$2.30	\$2.60	\$2.90	\$3.30	\$3.60
15	Manatí	\$1.05	\$2.00	\$2.30	\$2.65	\$2.95	\$3.30	\$3.60
6	Vega Alta	\$0.70	\$1.35	\$1.70	\$2.00	\$2.30	\$2.65	\$2.95
113	DTL East Right Lane	Dynamic price						
112	DTL East Left Lane							
17	Toa Baja	\$0.70	\$1.35	\$1.70	\$2.00	\$2.30	\$2.65	\$2.95
8	Buchanan	\$0.70	\$1.35	\$1.70	\$2.00	\$2.30	\$2.65	\$2.95

Table 2 - PR-22 toll pricing scheme for the WB direction

Plaza ID	Plaza Name	Toll Price per Class						
		1	2	3	4	5	6	7
18	Buchanan	\$0.70	\$1.35	\$1.70	\$2.00	\$2.30	\$2.65	\$2.95
111	DTL West Lane	Dynamic price						
7	Toa Baja	\$0.70	\$1.35	\$1.70	\$2.00	\$2.30	\$2.65	\$2.95
16	Vega Alta	\$0.70	\$1.35	\$1.70	\$2.00	\$2.30	\$2.65	\$2.95
5	Manatí	\$1.05	\$2.00	\$2.30	\$2.65	\$2.95	\$3.30	\$3.60
3	Arecibo	\$1.00	\$2.00	\$2.30	\$2.60	\$2.90	\$3.30	\$3.60
2	Factor	\$0.70	\$1.35	\$1.70	\$2.00	\$2.30	\$2.60	\$2.90
11	Hatillo	\$0.70	\$1.35	\$1.70	\$2.00	\$2.30	\$2.65	\$2.95

The toll rate charged for the use of the DTL is dynamically changed based on the average speeds of the median lanes. The pricing algorithm changes the toll charged to users based on maintaining a vehicle speed of 55 mph in the DTL even though the posted speed limit of the facility is 45 mph. The posted speed limit of 45 mph was established at the start of the operations of the DTL facility for safety reasons as the two median reversible lanes were separated by concrete barriers when going under two bridges. However, the general-purpose lanes have a posted speed limit of 55-mph along the freeway corridor which could present a paradox to the purpose of the DTL. The DTL pricing mechanism changes the toll rate every 5 minutes based on real time traffic conditions [Abertis, 2016]. The range of the variable toll rate has a minimum of \$1.70 to a maximum of \$4.95. The toll charged to the DTL users includes the \$0.70 fixed toll that is charged to GTL users at the Toa Baja Station. Therefore, the actual premium charged for the use of the DTL starts from the \$1 minimum to the maximum of \$4.25.

c. Traffic Flow Characteristics

The database used in this study included toll transactions recorded from the 13 GTL collection stations and the three DTL collection stations along freeway PR-22 for the year 2019. Each data file included information from each individual transaction recorded with the transaction number, transaction date, transaction time, transponder number, vehicle class, toll paid, toll station location, travel direction, toll station name, and lane number. The database contains 186,731,549 transactions from the 13 GTL collection stations, and 2,049,537 transactions from the three DTL collection stations.

The toll transaction data was analyzed to calculate basic traffic flow characteristics on the GTL and the DTL. The AADT values along PR-22 were estimated using the toll transactions recorded at each station. The AADT is defined as the average volume of traffic for a “one-day” period during the data reporting year. The FHWA recommends the American Administration of State Highway and Transportation Officials (AASHTO) method to estimate the AADT [Lokesh, 2019]. This method was chosen because it provides reliable estimates even when considerable days of data are missing or not recorded. The analysis of the 2019 data revealed that the PR-22 DTL was closed for traffic during some days of the year. Equation 13 shows the formula for the calculation of AADT from the AASHTO method as:

$$\frac{1}{7} \sum_{i=1}^7 = 1 \left[\frac{1}{12} \sum_{j=1}^{12} \left[\frac{1}{n} \sum_{k=1}^n [Volume_{ijk}] \right] \right] \quad (13)$$

where

Volume_{ijk} = daily traffic for day k of day of week i in month j

i = DOW (1, 2, ..., 7)

j = month of year (1, 2, ..., 12)

k = the first DOW in a month where data is available

n = number of days available for the DOW during that month

The result of the AADT calculation was a set of tables per toll station summarizing the monthly average daily traffic (MADT) for each day of the week (DOW) and the average traffic flow per DOW. Appendix C includes the AADT estimates from the toll stations on PR-22. Table 3 summarizes the AADT results for freeway PR-22 by toll location.

Traffic flow along PR-22 steadily increases as the freeway enters the SJMA. The highest AADT of 150,941 vpd was obtained for the Buchanan Toll Station located in the Municipality of Bayamón, the last station to the east of the freeway. The AADT values show the impact on traffic due to the reduction in population that occurred in Puerto Rico during the last decade. The highest AADT recorded for a PR-22

segment near the Buchanan Station was 218,501 vpd in 2012 [PRHTA, n.d.], a 36.5% higher from the 2019 value estimated for the Buchanan Station from the toll transaction data.

Table 3 - 2019 AADT per toll station in PR-22

Toll Station		Station Location	AADT (vpd)
EB direction	WB direction		
1	11	Hatillo	35,001
4	3	Arecibo	47,387
15	5	Manatí	56,500
6	16	Vega Alta	70,249
17: GTL 112 & 113: DTL	7: GTL 111: DTL	Toa Baja	98,987
8	18	Buchanan	150,941

The peak traffic periods for the DTL and GTL along the PR-22 were identified from the toll transaction data. The estimates were done using the year 2019 data with 5-minute intervals. Table 4 shows the weekday peak traffic periods for the GTL and the DTL for both directions. The morning peak period was identified from 5:40 to 7:35 a.m. and the afternoon peak period was identified from 3:20 to 5:05 p.m.

Table 4 - Weekday peak traffic periods

Toll Station (Direction)	Station ID	Traffic Flow (vph)	Peak Period
EB direction			5:40 – 7:35 am
Toa Baja DTL (EB)	113	572	6:40 – 7:35 am
Toa Baja DTL (EB)	112	427	6:35 – 7:30 am
Toa Baja GTL (EB)	17	3,107	5:40 – 6:35 am
Buchanan GTL (EB)	8	6,314	6:40 – 7:35 am
WB direction			3:20 – 5:05 pm
Buchanan GTL (WB)	18	6,486	3:20 – 4:15 pm
Toa Baja DTL (WB)	111	573	4:10 – 5:05 pm
Toa Baja GTL (WB)	7	3,155	4:05 – 5:00 pm

5. Analysis of Economics Measures

This chapter presents the analysis of the results from the online survey of freeway PR-22 users and the estimation of the price elasticity of demand and the value-of-time (VOT). The results also include the DTL usage factors and the WTP estimate from the Van Westendorp Price Sensitivity Meter.

a. Description of the Sample

A total of 518 responses were utilized for the analyses, which provided a survey error margin of 4.3%. The gender distribution for the sample was 50% females and 47.5% males. Figure 11 shows the age distribution of the respondents. The median age is 45 years old with a standard deviation of 14.5 years. The sample median age is slightly higher than the corresponding value of 43 years old for Puerto Rico as estimated by the U.S. Census Bureau in 2019 [U.S. Census, 2019]. The age range in the sample included respondents from 18 to 85 years old. In terms of ethnicity and race groups, about 87% of the respondents are Hispanic or Latino, 8% are White or Caucasian, and 5% are from other groups.

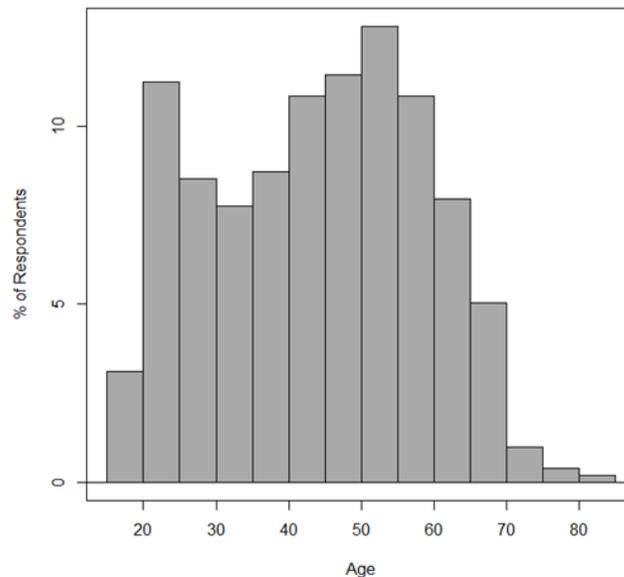


Figure 11 - Age distribution of survey respondents

Figure 12 shows the distribution of the education level achieved by the respondents. The major group (41%) of respondents stated having a bachelor's degree. Part of the survey advertisement was done by sending e-mail messages to the community of the two largest campuses, Mayagüez and Río Piedras, of the University of Puerto Rico. This fact could be related to 38% of the participants with either a master's or doctorate degree in the sample. The survey was administered online and participants from the two campuses cannot be identified directly, which might be a limitation of the sampling method used. As the population of interest is users of freeway PR-22, a tolled facility, this distribution could be indicative of a difference from the general population of the territory. The survey was also advertised on social media looking for residents and commuters from municipalities from the San Juan Metropolitan, Northern and Northwest regions, which have the highest potential for being users of the freeway and the DTL. Therefore, an analysis related to the location of the residence and place of work/study of the survey participants were made to identify the adequacy of the sample.

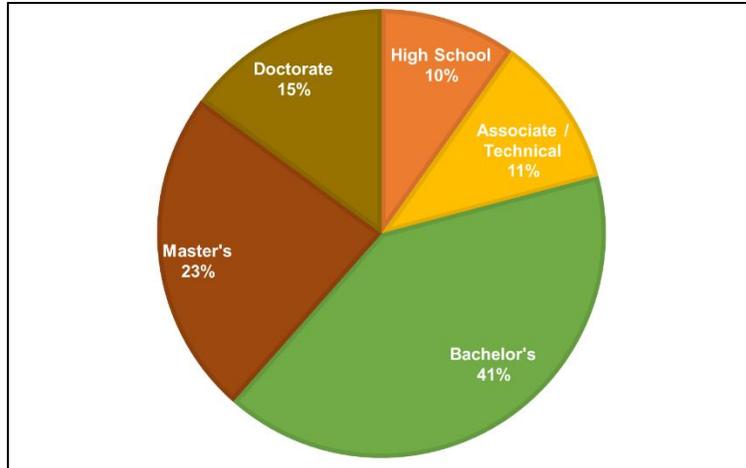


Figure 12 - Education level achieved by survey participants

Figures 13 and 14 show density maps of the location of the municipality of residence and the municipality of workplace/school of the respondents. The purpose of these two questions was to identify how many respondents in the sample had the potential for using freeway PR-22 as an alternative for their commute/school trips. Those persons living or working/studying near the PR-22 corridor are believed to be more exposed to the chance of selecting the DTL for their daily trips.

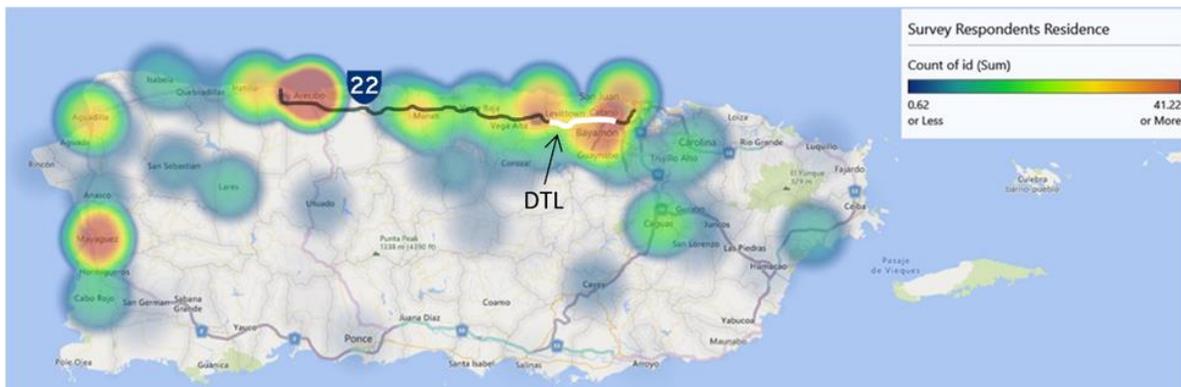


Figure 13 - Municipality of residence for survey participants



Figure 14 - Municipality of workplace / school for survey participants

As indicated by the dark red color, the regional distribution of the municipality of residence of the subjects is highly concentrated in the municipalities of Mayagüez, Aguadilla, Arecibo, Manatí, Vega Alta, Bayamón, and San Juan. The high presence of residents from Mayagüez in the survey makes sense due to the location of the UPRM. Nonetheless, 62.2% of the sample lives in a municipality near the PR-22 corridor, which presents a good chance of having respondents that know about the facility and have the potential of using the PR-22 DTL frequently for their trips toward the San Juan Metropolitan Area (SJMA).

Furthermore, the spatial distribution of the work/study place of the subjects is heavily concentrated in the municipalities of Mayagüez, Bayamón, and San Juan. About 65.1% of the sample works or studies in a municipality near the PR-22 corridor. Of the subjects that stated to work or study on a municipality near the PR-22 corridor, 78.5% of them either work or study in the SJMA. The heavy concentration of trip productions and attractions in the SJMA implies that the respondents have high exposure to the PR-22 and the DTL facility for either their work or study trips.

b. Factors for Using the PR-22 DTL

Several questions were included in the survey to identify factors for the selection of the DTL when making a trip on PR-22. The 76.4% of the participants stated to have used the DTL before. This result, in combination with the results for the residence and workplace locations, provides confidence that the respondents have experience using the DTL and know about its operation and pricing scheme. About 25% of the respondents who stated to have used the DTL have a frequency of use of at least once a week. About half of the DTL users stated to use it at least once a month. These results provide further evidence of the level of experience using the DTL. Not surprisingly, the stated frequency of use was reduced after the COVID-19 pandemic was declared in March 2020. Figure 15 provides the results of the stated frequency of use of the PR-DTL facility prior to and after the COVID-19 pandemic was declared in March 2020. The percentage change results shown in Table 5 confirm the COVID-19 pandemic negatively affected the quantity of high-frequency DTL users.

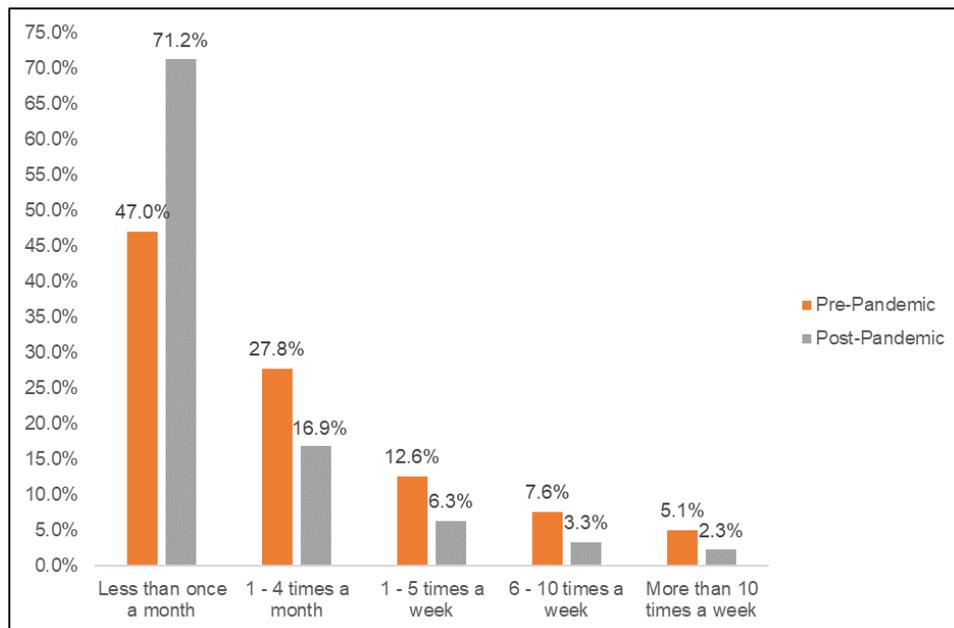


Figure 15 - Frequency of use of the PR-22 DTL before and after March 2020

Table 5 - Change in stated pre- and post-pandemic DTL usage frequency

Frequency	% Change
< once a month	+40.9%
1 - 4 times a month	-48.8%
1 – 5 times a week	-66.7%
6 – 10 times a week	-78.9%
> 10 times a week	-75.7%

Figure 16 shows the answers related to the moment when the DTL user decides to select the DTL. Almost half of the stated users of the DTL indicated they decide to use the facility when observing the traffic conditions on the freeway. Conversely, 21% of the DTL users stated to make the decision when receiving an alert from a trip routing or mapping application. Only 14% stated using the DTL price as an indicator of the traffic conditions ahead to make the decision. The price of the DTL is the only piece of information the freeway users receive in real time about the conditions on the managed lanes. No information about travel time savings, expected speeds, or quality of the trip on the DTL is provided to drivers to assist them in their decision. Might be the reason for the number of respondents that use a trip mapping application to make the decision to use the DTL, although it is not clear if these applications will provide a travel time estimate when selecting the DTL on PR-22.

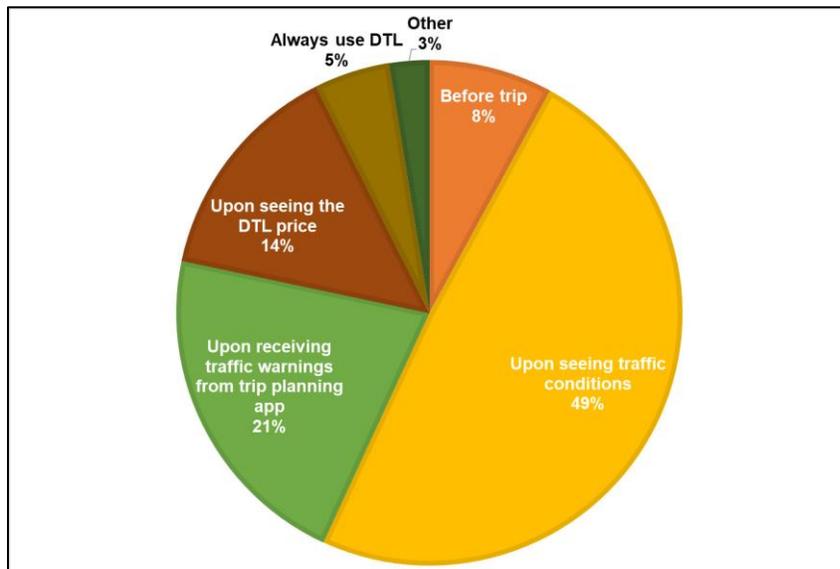


Figure 16 - Stated moment when drivers make the decision of using the DTL

Figure 17 shows the responses from DTL users when asked about the relative importance that six factors had on their decision to use the facility. Ninety-one percent of the user respondents indicated that the GTL Congestion was an important or very important factor in their decision to utilize the DTL. That level of response was the highest of the six factors. The next two factors with the highest importance level were Time Savings with 84% and Trip Urgency with 82% of the respondents selecting the important and very important categories. The DTL Price was the fourth factor selected, although still relevant with 74% of the respondents perceiving it as an important or very important factor in their decision to use the DTL. In contrast, Safety and Climate Conditions were the two factors with the lowest importance levels with 43% and 35%, respectively, indicating these two factors were not as important for users in their decision to use the DTL.

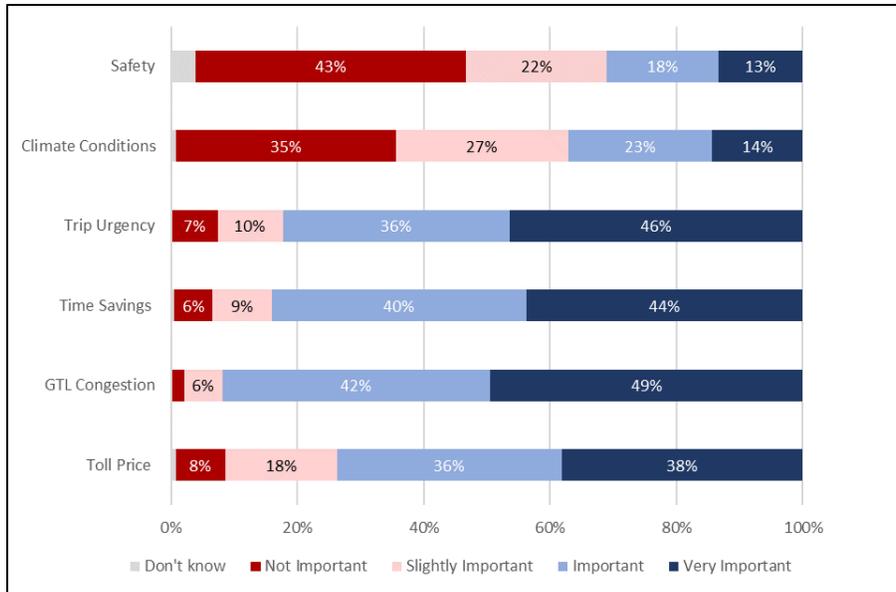


Figure 17 - Relevance of factors used when making the decision of using the DTL

A question was included to identify how many respondents receive reimbursement for the tolls paid during a road trip. Only 1.9% of the respondents indicated they received reimbursement of all toll expenses in all their trips, and 11.4% indicated to receive reimbursement for some of the trips. The reasoning for the question was that those freeway users that receive reimbursement of their toll expenses for all or part of their trips might be more willing users of the PR-22 DTL. Even so, 4.8% of DTL users stated to always use the facility when making a trip on freeway PR-22.

Figure 18 shows the frequency of use of the DTL with respect to trip purpose. More than half (53%) of the DTL users stated using the facility sometimes or always for work-related trips. In contrast, only 16% of the DTL users stated to use the facility sometimes or always when making study-related trips. The majority of DTL users (64%) indicated they select the facility sometimes or always for leisure related trips.

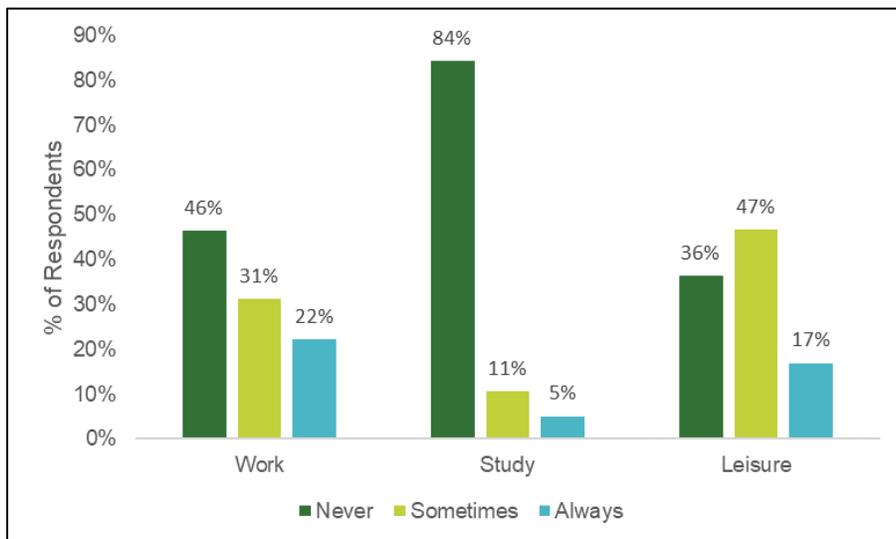


Figure 18 - Relevance of trip purpose when selecting the DTL

The possible factors for using the DTL was an assessment of the subject’s opinion about the facility. A Likert scale from 1 to 5 was used, with a value of 5 representing a “*very good*” opinion about the DTL, and a value of 1 representing “*a very bad*” opinion about the DTL. A value of 3 was considered “*neutral*.” Almost 45% of the subjects have a neutral opinion about the DTL, whereas 40% of the subjects have either a good or very good opinion about the DTL. The percentage of positive reaction to the DTL from the survey, as shown in Figure 19, might indicate that the respondents recognize its benefit in providing an alternative to traffic congestion in the corridor and the improvement in the quality of the freeway trip.

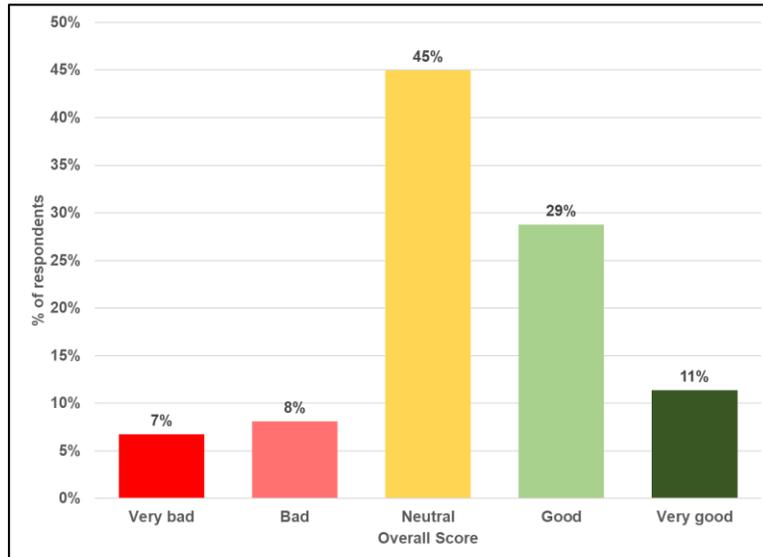


Figure 19 - Opinion about the PR-22 DTL

The perception of the DTL users about the reliability of faster trips in the facility and the perception of “good value” provided by the premium fee paid are shown in Figure 20. The majority of DTL users (64%) think that a facility is a reliable option for faster trips. On the contrary, 50% of the DTL users believe the facility does not provide a “good value.” This perception of negative value may point out to a users’ perception of low value in the WTP of DTL tolls in PR-22.

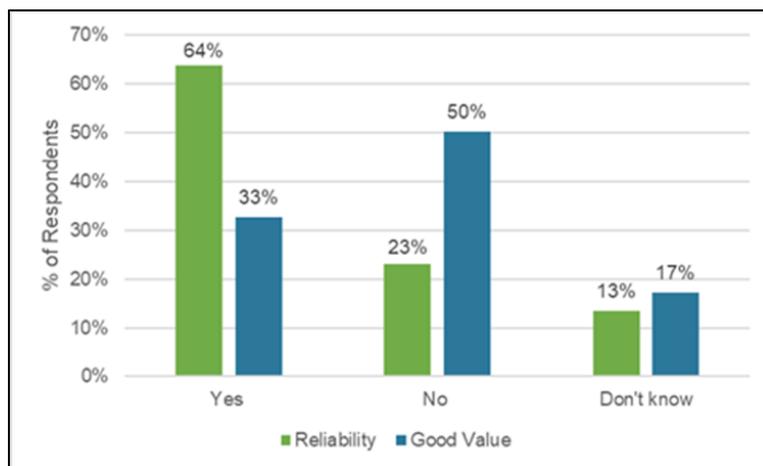


Figure 20 - Perceived reliability and good value of the PR-22 DTL

The survey included a question about the stated number of vehicle occupants when traveling on freeway PR-22. Although this question does not relate directly to the use of the DTL, the vehicle occupancy response could assist to quantify the potential for implementing a HOV strategy for the PR-22 segment, either a reduced fee or free cost for those vehicles with more than one occupant. About 15% of the freeway users stated to drive along PR-22 with more than one companion, whereas 42% stated they drive with one companion.

c. Willingness to Pay

The assessment of the WTP of the survey subjects was made using two methods: the Van Westendorp Price Sensitivity Meter (VWPSM) and the Stated Preference scenarios. The next two sections will provide a discussion of the results obtained from both methods.

i. Van Westendorp Price Sensitivity Meter

The VWPSM analysis performed during the project required the inclusion and creation of a survey instrument. As mentioned earlier, the main (four) questions of the analysis were included in the WTP section of said survey. A total of 518 subjects answered the VWPSM questions. A transitive price conditionality structure was used for the responses as suggested by Lipovetsky [2006]. This structure consists of excluding responses that do not follow a sequential and logical order between the four prices: *too cheap* \leq *cheap* \leq *expensive* \leq *too expensive*. After the inclusion of this condition, the total number of qualified responses from the survey was adjusted to 431.

Figure 21 shows the aggregate analysis for the VWPSM. The graph presents four curves and intersection points, as well as a rectangular shaded area encompassed by two of the intersection points. The curves are directly linked with the responses recorded in the survey. Nonetheless, the analysis modifies the *cheap* and *expensive* curves to obtain the (1-Cumulative%) value of the respective curves. These are denoted as the *not cheap* and *not expensive* curves. As per the graph, the intersection points that encompass the shaded area, represent the Price of Marginal Cheapness (PMC) and the Price of Marginal Expensiveness (PME) as boundaries of the range of acceptable prices. Prices found in this range are acceptable by consumers and thus are the price range of which travelers are willing to pay for the PR-22 DTL price.

From the aggregate analysis including all respondents, the WTP range was found to be from \$1.00 to \$2.79. The Optimal Price Point (OPP) is \$1.46, in which the least resistance to consumption by PR-22 users is to be expected. The WTP range is well below the \$4.95 maximum toll price established for the PR-22 DTL. These results for the WTP were anticipated after observing that only 33% of users stated that the DTL facility provided a good value for the price paid.

Figures 22 and 23 show the graphical analyses of the VWPSM based on prior experience with the DTL. There are differences between users and non-users of the DTL, in which the users have higher PMC, PME, and OPP values. The users and non-users had WTP ranges of \$0.95 to \$2.87, and \$0.74 to \$1.89, respectively. An observation to be made is that the VWPSM does not average the sample size in the determination of the PMC and PME ranges, thus instances where the aggregate results may not be bounded by their sub-segment results can be expected. Although differences in WTP ranges between users and non-users were expected, we believe that is of great relevance considering that we do not wish to rely solely on the WTP assessment of active and passive users of the DTL, but we are interested in also capturing the ranges of individuals that have not previously utilized the facility and may have a lesser bias or price anchoring to the existent toll prices.



Figure 21 - Aggregate analysis of the Van Westendorp Price Sensitivity Meter

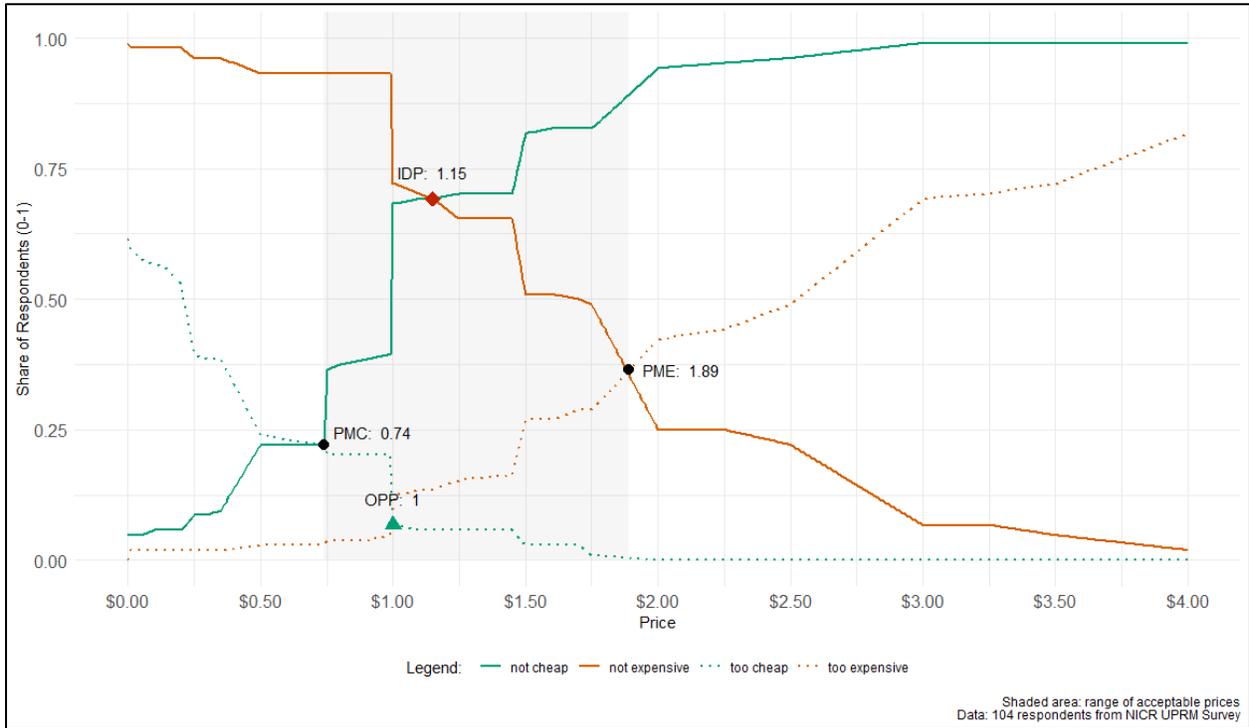


Figure 22 - Van Westendorp Price Sensitivity Meter plot for non-users

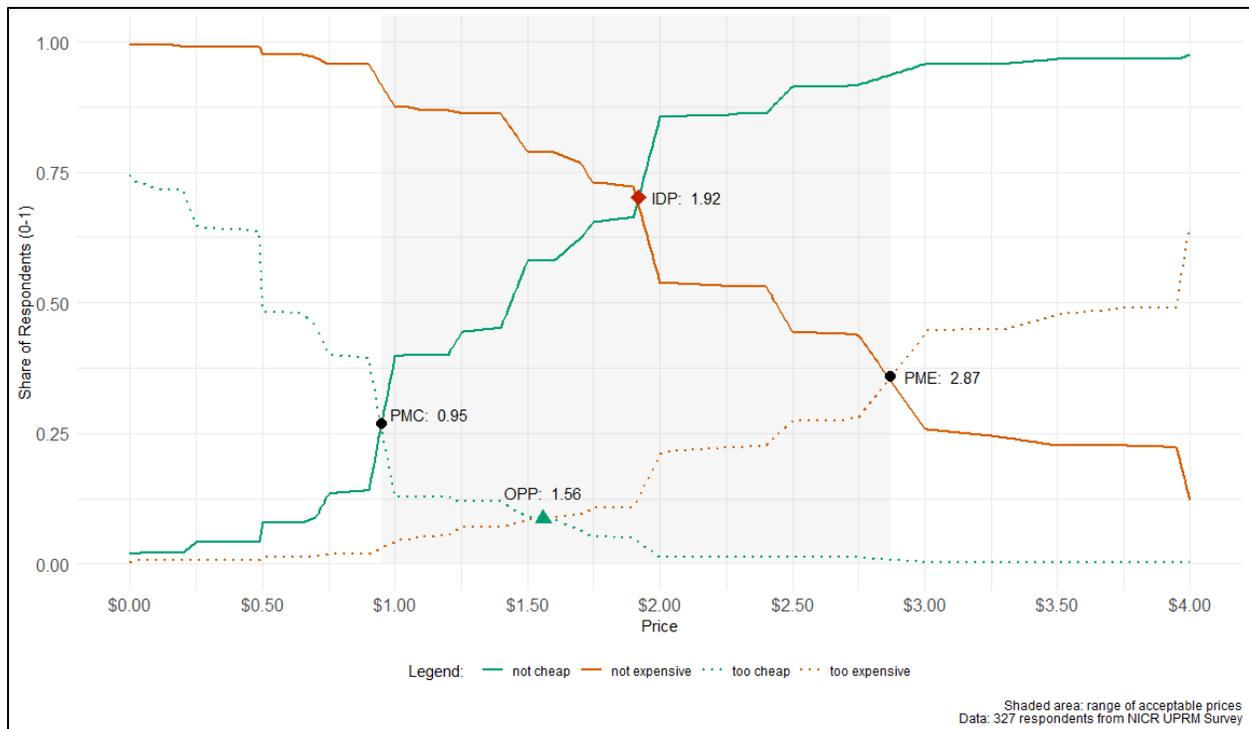


Figure 23 - Van Westendorp Price Sensitivity Meter plot for users

One of the study objectives was to contrast and compare different WTP ranges based on sociodemographic variables. Utilizing the sociodemographic profile obtained from the survey, the VWPSM analysis was performed for the different socioeconomic variables and their respective segments and groups. Table 6 presents the complete analysis of each group based on the variables of income, education, gender, and age. Each group has its respective values for PMC, PME, IPP, and OPP, presented along with their split distribution of values for users and non-users. Some groups are omitted from the table due to their low sample size ($n \leq 10$), which include the variable “income higher than \$150,000”, and the “Other/prefer not to say” response to the gender question. In some instances, the PME can be used as a proxy of the reservation price, since it is the highest price the consumer is willing to pay to use the DTL.

The results for the income variable provide interesting observations regarding income levels and their respective WTP ranges. The distribution of survey responses related to income in comparison with the 2019 American Community Survey estimates for Puerto Rico are presented in Figure 24. An increase in the income of the subject was found to be not necessarily related to a higher WTP range. Reservation prices, except for the *less than \$10,000* (aggregate) group, exhibited an opposite behavior to income levels. Among the user groups, the highest reservation price of \$2.87 was observed for the *less than \$10,000* subject group. This price is consistent to the \$2.86 price found for the \$25,000 - \$49,999 group and the \$2.85 found for the \$50,000 - \$74,999 group. The lowest PMC value of \$0.76 was reported for the \$75,000 - \$149,000 (aggregate) group, the highest level of income in the sample. A similar phenomenon was reported by a WSDOT study of the users of the I-405 Express Toll Lanes, in which an inverse relationship was observed between the toll price paid and the income levels [Leung et al., 2019]. Similar results in the relationship of WTP values and income levels were reported by Abdulbieh et al., [2018] and Li et al. [2002].

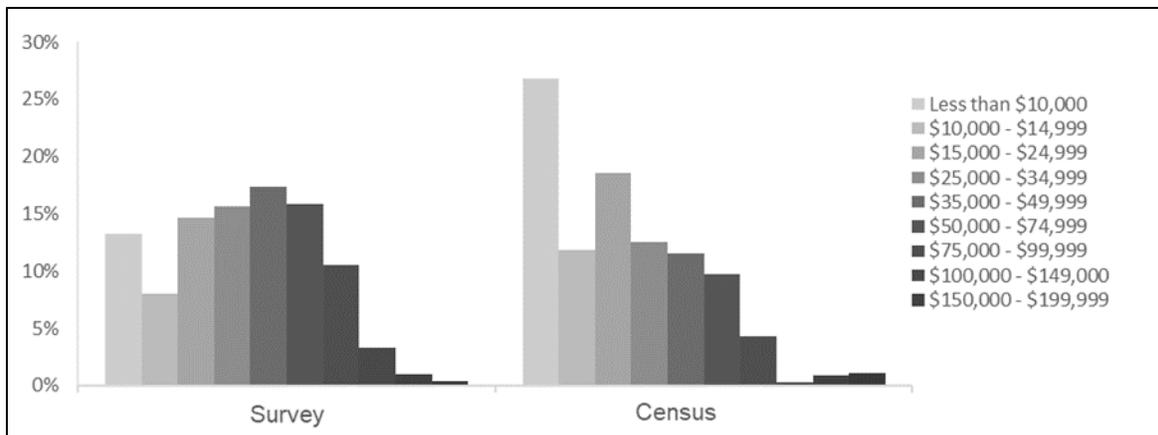


Figure 24 - Income brackets from survey vs. 2019 American Community Survey

The education level achieved by the subject exhibited no clear pattern with respect to the WTP ranges. Furthermore, females provided higher levels of WTP ranges in all WTP ranges, in all the rich the higher the age group, the higher the reservation price and PMC values, except for the age group of +65 years old. This deviation could point to a larger number of retirees in this group of analysis, in which trip urgency and trip purpose could have a lessening effect in their WTP range.

Furthermore, as per the survey question regarding “good value for its use” (Figure 20), the overall negativity in user respondents to the ability of the DTL to provide good value could directly affect the WTP ranges obtained in the analyses. Given the cheap VWPSM question of the analysis elicits the respondent’s price assessment of “good value” for the toll price of the DTL, it is expected that the respondents do not consider overall higher price levels in this question. Therefore, the median value of the cheap VWPSM question is \$1.70 for user respondents that answered “yes” in the “good value for its use” question when compared to the median value of \$1.00 in those that answered “no” in the same question. Thus, pointing explaining some low WTP ranges reported in this section.

An important observation of the results in Table 6 is that the survey questions only elicit DTL prices. This is important since the price reflected in the DTL gantry signaling includes the fixed \$0.70 toll rate of the GTL. For example, when the DTL price shows \$1.70, the implied premium toll for utilizing the DTL is \$1.00. The respondent may have a bias in the perception of his/her WTP for the DTL price since the subject may also be pricing in the GTL price as they may see it “unavoidable” due to the lack of comparable routes to the PR-22 freeway. In contrast, non-DTL users may not be aware of the inclusion of the fixed GTL price, which could explain lower values in some instances. The survey does not provide the data to validate this possible explanation.

Table 6 - Van Westendorp Price Sensitivity Meter for sociodemographic variables

Variables	n	PMC	PME	IPP	OPP
Aggregate	431	1.00	2.79	1.73	1.46
Users	327	0.95	2.87	1.92	1.56
Non-users	104	0.74	1.89	1.15	1.00
Income †					
Less than \$10,000	51	0.91	2.50	1.65	1.15
Users	30	0.95	2.87	1.92	1.56
Non-users	21	0.80	2.01	1.44	1.00
\$10,000-\$24,999	92	1.00	2.78	1.87	1.61
Users	68	0.92	2.71	1.72	1.00
Non-users	24	0.65	1.94	1.37	1.00
\$25,000-\$49,999	131	1.00	2.76	1.50	1.01
Users	105	0.98	2.86	1.93	1.92
Non-users	26	0.39	1.48	1.00	1.00
\$50,000-\$74,999	70	0.90	2.66	1.82	1.51
Users	54	0.84	2.85	1.91	1.21
Non-users	16	0.88	2.38	1.50	1.50
\$75,000-\$149,999	53	0.76	2.51	1.39	0.99
Users	41	0.91	2.74	1.84	1.51
Non-users	12	0.35	1.42	0.91	1.01
Education					
High School	40	0.80	2.70	1.75	1.09
Users	26	0.83	2.73	1.79	1.09
Non-users	14	0.60	2.44	1.60	1.00
Associate/Technical Degree	43	1.00	2.44	1.71	1.10
Users	31	0.90	2.83	1.92	1.76
Non-users	12	0.67	1.50	1.00	1.00
Bachelor's Degree	177	1.00	2.46	1.65	1.45
Users	133	0.95	2.78	1.74	1.48
Non-users	44	0.48	1.90	1.19	1.00
Master's Degree	105	0.96	2.86	1.80	1.55
Users	85	0.97	2.93	1.85	1.73
Non-users	20	0.75	1.84	1.25	1.06
Doctoral Degree	66	0.80	2.79	1.77	1.01
Users	52	0.85	3.20	1.84	1.40
Non-users	14	0.38	1.63	0.92	0.84
Gender †					
Female	217	1.00	2.89	1.93	1.46
Users	156	0.97	2.99	1.96	1.74
Non-users	61	0.50	1.92	1.00	1.00
Male	203	0.93	2.44	1.50	1.21
Users	164	0.94	2.49	1.70	1.44
Non-users	39	0.65	1.85	1.21	1.00
Age Group					
18-24	56	0.92	2.74	1.72	1.25
Users	38	0.94	2.81	1.92	1.17
Non-users	18	0.68	1.94	1.27	1.27
25-44	133	0.92	2.78	1.74	1.44
Users	102	0.93	2.82	1.91	1.45
Non-users	31	0.57	2.34	1.39	1.26
45-64	184	1.00	2.83	1.91	1.25
Users	137	0.92	2.96	1.94	1.72
Non-users	47	0.47	1.50	1.00	1.00
65+ †	25	0.86	2.38	1.50	1.72

† Variable group or segment not presented due to failure to meet inclusion conditionality.

ii. Stated Preference Scenarios and Value of Time

A binary logit model was developed to study the choices the individuals made when faced with hypothetical scenarios in which they need to decide whether to use or not use the DTL. This model was used to estimate the value-of-time (VOT) of the respondents. The data utilized in this analysis was obtained from the stated preference scenarios provided in the WTP section of the survey. Nine scenarios were shown to each participant. Each scenario was characterized by a toll price and a travel time savings (TTS). Toll prices included \$1.00, \$4.00, or \$8.00, while TTS included 1 minute, 7 minutes, or 15 minutes. The subject analyzed the given conditions on each scenario and provided a “YES” or “NO” answer based on their WTP for the DTL and the expected benefits on a morning commute trip at 7 a.m. going in direction to San Juan. Figure 25 shows a screen capture of the survey questions, in Spanish, related to one of the scenarios. The three scenarios shown in the figure were related to the DTL price of \$1.00.

CARRIL EXPRESO

SOLO 

22

TARIFA

\$ 1.00

VIOLADORES SERÁN MULTADOS

Dirección del Viaje:
Hacia San Juan

Fecha/Hora:
**Día de Semana
7:00 AM**

¿Pagaría \$1.00 por el carril expreso si se ahorra 15 minutos en su tiempo de viaje? *

Si

No

¿Pagaría \$1.00 por el carril expreso si se ahorra 7 minutos en su tiempo de viaje? *

Si

No

¿Pagaría \$1.00 por el carril expreso si se ahorra 1 minuto en su tiempo de viaje? *

Si

No

Figure 25 - Example questions of the stated preference experiment

The 518 subjects generated 4,662 stated preference responses. A test was used to determine if the subjects were logical in their responses. A total of 505 subjects and 4,545 scenario responses were kept for the analysis after the logic test. It is important to point out that the questions were available to all the subjects and did not include a DTL user conditionality. Table 7 presents the percentage of subjects that selected the DTL per each scenario. As expected, the percentage of DTL selection increases with higher TTS and decreases as the dynamic toll rate increases. The highest percentage of 87.5% for selecting the

DTL was observed for the scenario with the largest TTS and lowest DTL price. In contrast, the lowest percentage of DTL selection of 0.4% was found for the scenario with the lowest TTS and highest DTL price.

Table 7 - Respondents that Selected DTL for Each TTS and Price Combination (%)

Travel Time Savings (min)	DTL Price \$1.00	DTL Price \$4.00	DTL Price \$8.00
15	87.5	29.3	5.8
7	45.4	10.4	2.3
1	10.6	1.5	0.4

The deterministic utility for the DTL alternative was specified using the price and TTS information and dummy variables related to the respondent’s attributes. The deterministic utility for the GTL alternative was a constant, that for estimation purposes was set to zero. The dummy variables included in the analysis were computed based on data collected from the sociodemographic profile of the survey. The model includes sociodemographic variables of age, income, and gender. In addition, a user dummy variable was included, which had a value of one (1) if the person stated to use the DTL before. The age variable was divided into a binary variable based on the Puerto Rico median age of 44 years [U.S. Census, 2020]. The upper data bin included subjects with 45 years and older and was defined with a value of one (1) for the dummy variable. The gender variable was defined as a binary variable using a male subject as taking the value of one (1). Income dummy variables were defined using income brackets. Since the income variable is collected from the survey in the form of ordinal ranges of income, three different income categories were created. These categories were based on the Puerto Rico Alternate Basic Tax and the Personal Income Tax Rate brackets which aligned with the income brackets of the U.S. Census American Community Survey [PWC, 2020; U.S. Census, 2020]. The classifications and their income bracket ranges were: *Low-Income* (less than \$10,000 - \$24,999), *Mid-Income* (\$25,000 – \$74,999), and *High-Income* (\$75,000 – \$200,000 or more). The *Mid-Income* and *High-Income* dummies were included in the models.

The “full” model, including all the dummy variables above-mentioned and the alternative attributes, is presented in Equation 14:

$$V_{GPL} = ASC_{GPL} \tag{14}$$

$$V_{DTL} = ASC_{DTL} + \beta_{Cost} * DTL_{Cost} + \beta_{TTS} * DTL_{TTS} + \beta_{User} * DM_{User} + \beta_{Age} * DM_{Age} + \beta_{HiIncome} * DM_{HiIncome} + \beta_{MidIncome} * DM_{MidIncome} + \beta_{Male} * DM_{Male}$$

where

V_i : deterministic utility functions ($i = \{ML, GPL\}$)

ASC: alternative specific constant

DTL: attributes of the alternatives

DM: decision maker user characteristics

In addition to the full model, four more models were considered. The base model only considered the cost and TTS variables of the scenarios. The user model included the user dummy variable to the base model. The age model included the age dummy variables in the user model. Lastly, the income model included the income dummy variables in the age model. The models were estimated using Biogeme [Bierlaire, 2020]. The calibration results of the regression models are presented in Table 8.

Table 8 - Estimation results for binary logit models

Parameter	Models				
	Base	User	Age	Income	Full
Cost	-0.704 (-25.2)	-0.715 (-25.3)	-0.717 (-25.3)	-0.717 (-25.3)	-0.720 (-25.3)
Travel Time Savings	0.251 (25.1)	0.256 (25.1)	0.256 (25.1)	0.257 (25.1)	0.258 (25.1)
User		0.780 (6.45)	0.781 (6.45)	0.781 (6.45)	0.844 (6.88)
Age (Upper Median)			-0.239* (-2.47)	-0.216* (-2.47)	-0.251* (-2.54)
High-Income				-0.803 (-7.51)	-0.730 (-6.71)
Mid-Income				-0.602 (-8.53)	-0.567 (-7.97)
Male					-0.332 (-3.36)
Constant	1.40 (13.4)	2.02 (13.8)	1.90 (12.4)	1.29 (11.6)	1.20 (10.4)
No. Obs.	4545	4545	4545	4545	4545
ρ^2	0.559	0.566	0.567	0.567	0.569
$\bar{\rho}^2$	0.558	0.565	0.565	0.565	0.566
VOT (\$/hr)	21.42	21.46	21.46	21.47	21.47

t statistic in parentheses

* $p < 0.01$, all others $p < 0.001$

As expected, the Travel Time Savings (TTS) coefficient was estimated with a positive sign, meaning that higher values of TTS would make it more likely that an individual to select the DTL. Furthermore, the Cost coefficient (DTL price) is negative, which indicates that higher DTL prices (i.e., costs of travel) make it less likely for an individual to select the DTL. These results are similar for all models, in which minimal variations in the magnitude of the coefficients are observed between them.

Subjects that have used the DTL at least once make it more likely for them to select the managed lanes relative to non-users. In fact, the user parameter has the largest absolute magnitude of all the user characteristics coefficients.

Subjects with an age higher than 45 years old (i.e., Puerto Rico’s median age) are less likely to select the DTL relative to those below the median age. This relationship is also reported by Li et al. [2002], in which there is a negative relationship between using managed lanes and age.

Income parameters for the two dummy variables also reflect a negative relationship. Thus, subjects with incomes in the *Mid* and *High* categories are less likely to select the DTL relative to those in the *Low-Income* category. This relationship was described by Leung et al. [2019] in which users with higher incomes were less willing to use the managed lanes at higher tolls. Li et al. [2002] point to inconsistencies and non-linear trends between income and intent to use a managed lane. Moreover, Li et al. [2002] found that the lowest income bracket population of less than \$25K were the most likely to use managed lanes.

Lastly, males are less likely to select the DTL relative to females. Abdulibieh et al. [2018] had similar findings in their model for managed lanes in Dubai. This result also bears some resemblance to our VWPSM results in which females had higher WTP ranges in comparison to males.

Based on the estimated parameters of cost and time variables the VOT was determined to be \$21.47 for the full model, which is only 0.2% higher than the lowest VOT obtained. The estimates are considerably larger than the estimates for local personal travel of \$10 per hour established in the Puerto Rico Long-Range Multimodal Transportation Plan [PRHTA, 2018]. One distinction to be made from these values is that the VOT calculated in this study is based on the cost and time parameters obtained from the full model. Thus, the VOT estimate is for the subjects who selected the DTL. The literature provides evidence in support of inflated VOT values for HOT Lanes and variable toll roads. Janson and Levinson [2014] point to higher-than-average VOT values in HOT lanes users since most travelers along a facility do not use the managed lanes. Another possible reason involves a distorted perception in which drivers overestimate their time savings with respect to reality [Janson and Levinson, 2014].

d. Price Elasticity of Demand and Demand Curves

An objective of this study was to determine demand curves from the PR-22 toll transaction data. The guidelines for quantity demanded and price variables were used as per the Economics: Pricing, Demand, and Economic Efficiency [FHWA, 2008b] to plot the travel demand curves. The estimated DTL traffic share (ML Share) was calculated as shown in Equation 15. The ML Share measures the quantity-demanded data, as referenced by Janson and Levinson [2014], and the price/cost data from toll prices.

$$ML\ Share = \frac{Q_{ML}}{Q_{ML} + \sum Q_{GTL}} \quad (15)$$

where

Q_{ML} = Vehicular flow in the managed lanes (ML)

Q_{GTL} = Vehicular flow in the general-toll lanes (GTL)

Intervals of five minutes were used for the calculation of the ML Share, like the update interval of the DTL price algorithm. Thus, data for the demand curves and the elasticity calculations was established for 5-minute intervals [t:t+5] during the morning and afternoon operating hours of the DTL. As the PR-22 DTL has a reversible operation, separate analyses were done for the morning operation (EB direction) and the afternoon operation (WB direction). Scatter plots were made using the average toll price paid and the average ML Share for each five-minute interval during the operations schedule of the DTL. Figure 26 presents the scatter plots for the EB direction (a) and the WB direction (b), respectively, using the average values of the 5-minute periods from the year 2019.

An observation from these curves is that they both exhibit a positive slope, suggesting a direct relationship between price and quantity demanded. Janson and Levinson [2014] reported similar findings in their I-394 MnPASS study. Although the first impression might suggest a violation of the general law of demand, studies have pointed out that the effect of congestion expectation and implied TTS for utilizing the DTL could increase usage in periods where toll prices are also increasing. These factors may induce the driver's decision to proactively use the managed lanes under the perception that an increase in the DTL price points to higher traffic congestion along the GTL. Given that the results pointed out that the congestion on the GTL is the most important factor in the decision for using the DTL, this perception could be even stronger among PR-22 DTL users. This behavior does not necessarily suggest a general law of demand violation, but an increase in the level of demand [Abulibdeh et al., 2018; Janson and Levinson, 2014].

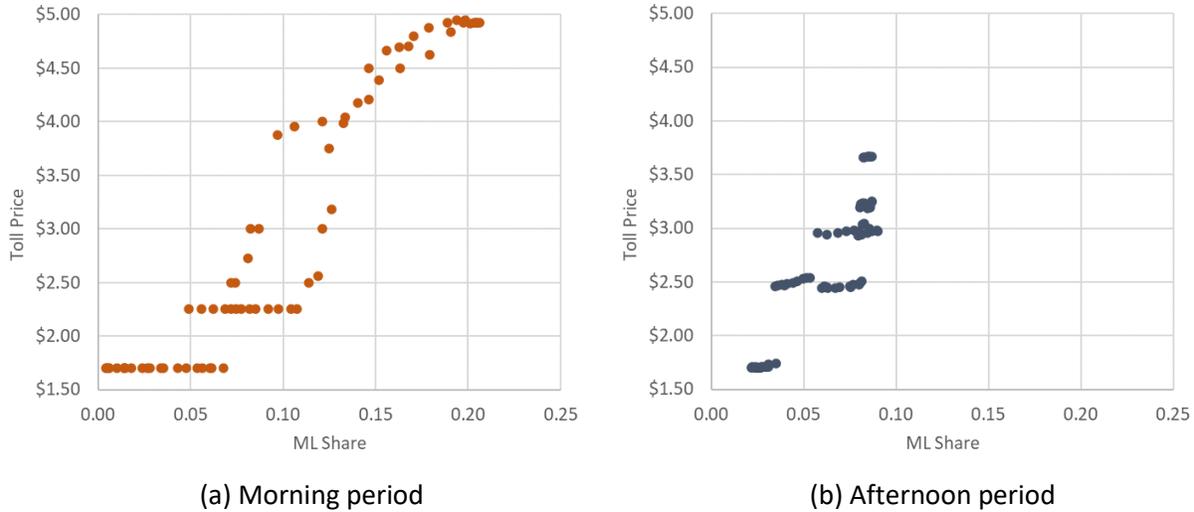


Figure 26 - DTL price paid vs. ML Share for the morning and afternoon periods

The price elasticity of demand for the PR-22 DTL was estimated from the analysis of the toll price paid and the traffic volumes. Table 9 presents descriptive statistics for the two variables per travel direction. As previously indicated, the DTL price paid and the ML Share variables have higher mean values for the DTL morning operation than for the afternoon operation.

Table 9 - Descriptive statistics for DTL price paid and ML Share

	Eastbound (a.m.) (Obs = 16,554)		Westbound (p.m.) (Obs = 20,904)	
Variable	Mean	Std. dev.	Mean	Std. dev.
DTL Price, \$	3.22	1.29	2.65	0.723
ML Share	0.169	0.092	0.063	0.031

The Janson and Levinson [2014] approach was applied to calculate the elasticity utilizing toll price and the ML Share datapoints in five-minute intervals. A double-log model was estimated to determine the price elasticity of demand (ϵ) for the PR-22 DTL. The model calibration results are shown in Table 10. The morning EB data include 16,554 observations, while the afternoon WB data include 20,904 observations. The analysis yields an $\epsilon = 1.21$ for the morning direction and an $\epsilon = 1.66$ for the afternoon direction. Since both $\epsilon > 1$, the price elasticity of demand is elastic for both operations. These results can be interpreted as if the DTL price increases by 1% on the morning and afternoon periods, then the ML Share increases by 1.22% and 1.66%, on average, respectively.

Table 10 - Log-Log Regression of PR-22 DTL Price and Traffic Data

Parameter	Morning Operation	Afternoon Operation
DTL Price	1.21 (140.2)	1.66 (153.6)
Constant	-3.27 (-287.4)	-4.49 (-385.6)
Observations	16,554	20,904
R ²	0.587	0.567

t statistic in parentheses
all parameters with *p*-values < 0.001

The difference in elasticity between the morning and afternoon operations implies that users are more inclined to use the DTL given a price increase when compared to morning users. Burriss et al. [2012] point to higher VOT values in the afternoon when compared to morning peak hours. This could explain the higher percentage increase in DTL usage in the afternoon when compared to the response of an equal toll price percentage increase in the morning.

The results seem to deviate from studies' consensus of inelastic values. An important observation is that the PR-22 DTL is not classified as a HOT lane in which HOV does not pay the toll for access and single-occupancy vehicles do [Brent and Gross, 2017]. This is a clear distinction for the PR-22 DTL as all users pay the same premium fee. This, along with other factors such as historic and cultural perception of toll roads and facilities in Puerto Rico, as well as the lack of close substitutes, could explain this deviation.



6. Analysis of Performance Measures

This chapter presents the results from the analysis of the seven performance measures selected to evaluate the efficiency of the PR-22 DTL. Basic traffic flow parameters of vehicle counts and speeds were obtained from the toll transaction data to calculate the Travel Time Index, the Travel Time Savings, the Planning Time Index, the Planning Time Index Benefit, the Ability of Toll to Impact Congestion, the Speed Threshold, and the Dominance Indicators.

a. Traffic Counts, Average Speeds, and Toll Paid

The toll transaction data was used to calculate average values at 5-minute intervals of the vehicle counts, vehicle speeds, and DTL price paid. These variables were used to assess the traffic flow patterns in the toll facility and calculate the performance measures. Figure 27 shows the average traffic counts and the DTL price paid per 5-minute period for the morning operations. Data from holidays and weekends, when the DTL was either open only for the EB direction or it was closed to traffic, were not included.

The plots in Figure 27 show the average behavior for the morning traffic flow on the suburban freeway. The peak traffic flow for the freeway is observed at around 6:25 a.m. with 390 vehicles for the 5-minute period. At that time interval, the traffic share of the DTL is 25.6%. The DTL traffic peak occurs about 25 minutes later, with 121 vehicles / 5-min, for a 32.9% traffic share. These percentages of traffic share in the DTL demonstrate the facility is being used considerably by PR-22 users. Data from Liu et al. [2011] for two express lane facilities (SR-91 and the I-15 FastTrack) show daily ML Share values of about 11-12%.

For the 40-minute period from 6:20 a.m. to 7:00 a.m., the traffic using the DTL continues to grow, whereas traffic on the GTL, and the total traffic on the EB direction of the freeway, is diminishing. As traffic on the DTL increases, the premium fee paid for the use of the median lanes increased. As a result of this behavior, the maximum price of \$4.95 for the DTL is established by the algorithm from 6:45 a.m. to 7:35 a.m. After the peak is reached, traffic on the DTL steadily decreases for the duration of the morning period. The pricing algorithm takes about 80 minutes to reach the maximum DTL price when traffic is increasing and about 135 minutes to change from the maximum to the minimum value when traffic is decreasing in the morning period.

The corresponding behavior of the vehicle speeds on PR-22 during the morning period demonstrates the dynamic operation of the DTL. The average vehicle speeds in Figure 28 were estimated using the transaction data for vehicles that passed through two consecutive toll stations. The formula used for the vehicle speeds was the distance between the two toll collection stations divided by the difference in time from the two toll transactions from the same vehicle. A Python coding was created to construct the trip chain for each vehicle that went through the two consecutive toll stations using the transponder number. Vehicle speeds for the GTL in the EB direction were calculated using the toll transactions registered between the Toa Baja and the Buchanan stations located approximately 7 miles apart. The individual vehicle speeds for the DTL in the EB direction were calculated using the transactions from the toll stations 112 and 113 at the DTL entry points and the Buchanan Toll Station located approximately 7.8 miles apart. Vehicle speeds for the GTL lanes in the WB direction were calculated using the transactions between the Buchanan and the Toa Baja stations. Vehicle speeds for the DTL WB direction were not calculated because the two consecutive toll stations, the DTL entry point, and the Vega Alta Station, are approximately 12.5 miles apart and far exceeding the length of 7.7 mi of the DTL facility.

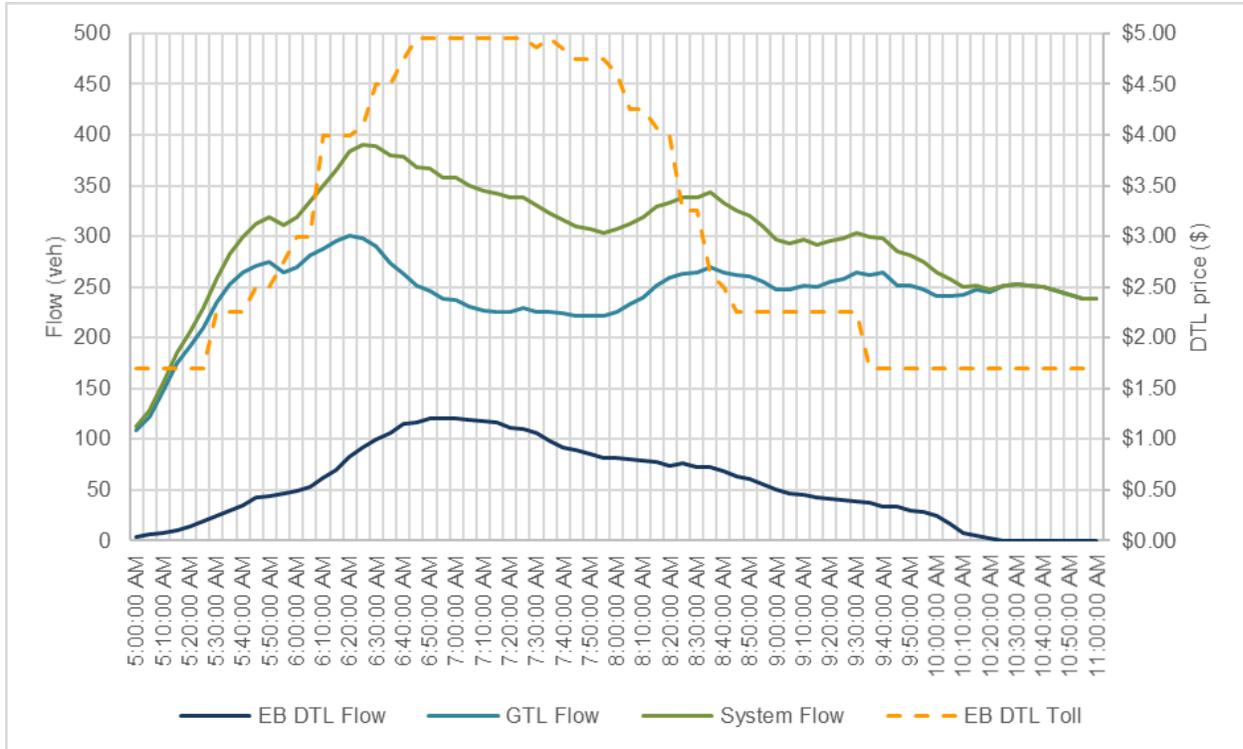


Figure 27 - GTL and DTL traffic flows and DTL price for EB direction

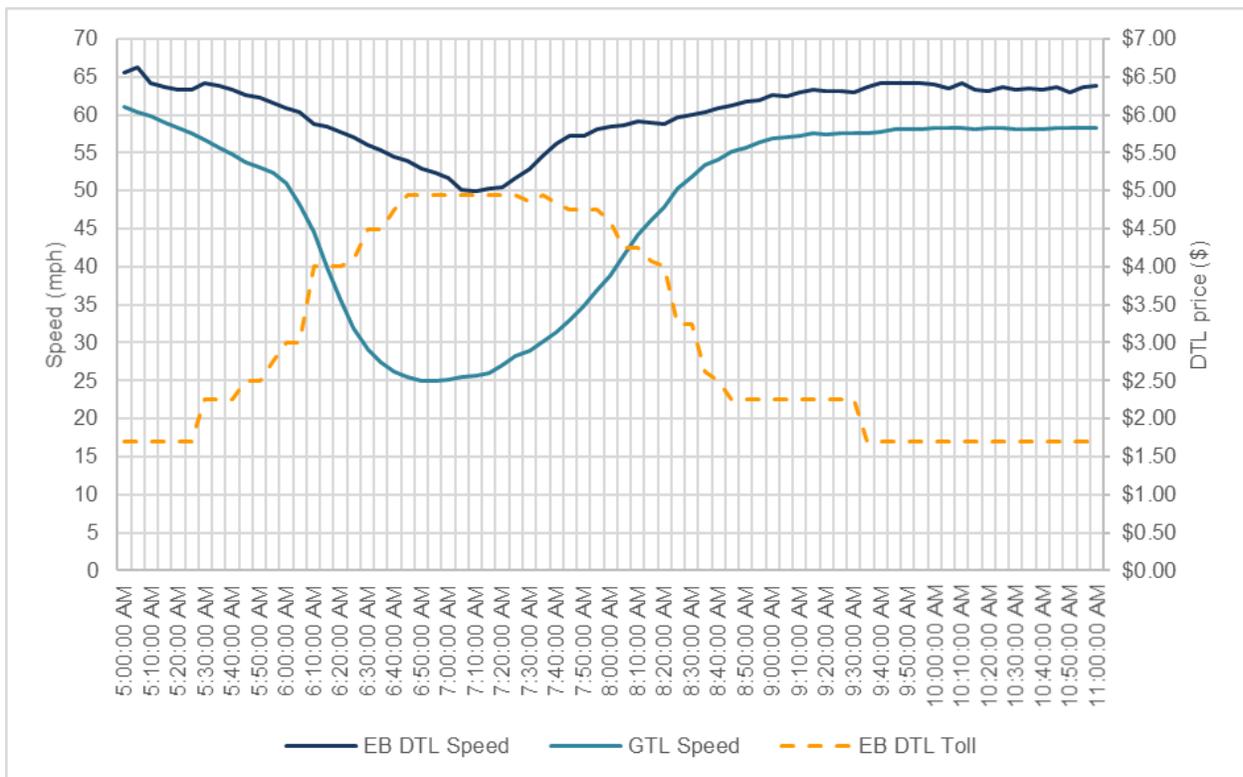


Figure 28 - Weekday GTL and DTL vehicle speeds and DTL price paid for EB direction

The average speeds degrade on the facility as traffic flow increases on both the GTL and the DTL. The pricing algorithm for the DTL behaves as expected, establishing a higher price as traffic increases, (i.e., as speeds are reduced on the DTL) and reduces the price on the DTL as traffic diminishes, (i.e., speed improves on the DTL). The speed degradation on the GTL occurs at a faster rate and generates a much larger reduction in speed than for the DTL.

The observed reduction in the average speed for the GTL is 35 mph, whereas is approximately 15 mph for the DTL. The average speed on the GTL goes from a top value of 60 mph at about 5 a.m. to a minimum value of 25 mph at about 6:55 a.m. Average speeds on the GTL reach a plateau of 58 mph at about 9 a.m. that continues for the rest of the morning period. The minimum average speed on the DTL of 50 mph is reached at about 20 minutes after the top price of \$4.95 is reached. The minimum speed on the DTL is then maintained for about 15-20 minutes approximately. The average speed on the DTL then steadily increases until reaching a plateau of about 52-64 mph for the remaining morning period. The difference in average speeds between the GTL and the DTL is about 5 mph before and after the peak period. Keep in mind that the posted speed limit for the EB direction is 40 mph on the DTL and 55 mph for the GTL, so there could be a potential speeding behavior on the facility. As the vehicle speeds analyzed in this study are estimated values based on two points of a trip, and not all vehicles in the traffic flow were considered, these results cannot be interpreted or related to the actual speed limit compliance on the freeway facility.

Figure 29 shows the traffic share, in percentage, for the DTL against the DTL price paid per 5-minute periods during the morning period. The data on the figure reflects the increasing trend to analyze how traffic on the DTL is proportionally increasing. As observed from the data, the highest traffic share for the DTL occurs at 7:10 a.m. with 34.2% of the total traffic on the EB direction of PR-22. As expected, the highest traffic share corresponds to the period when the DTL price reaches the maximum price of \$4.95.

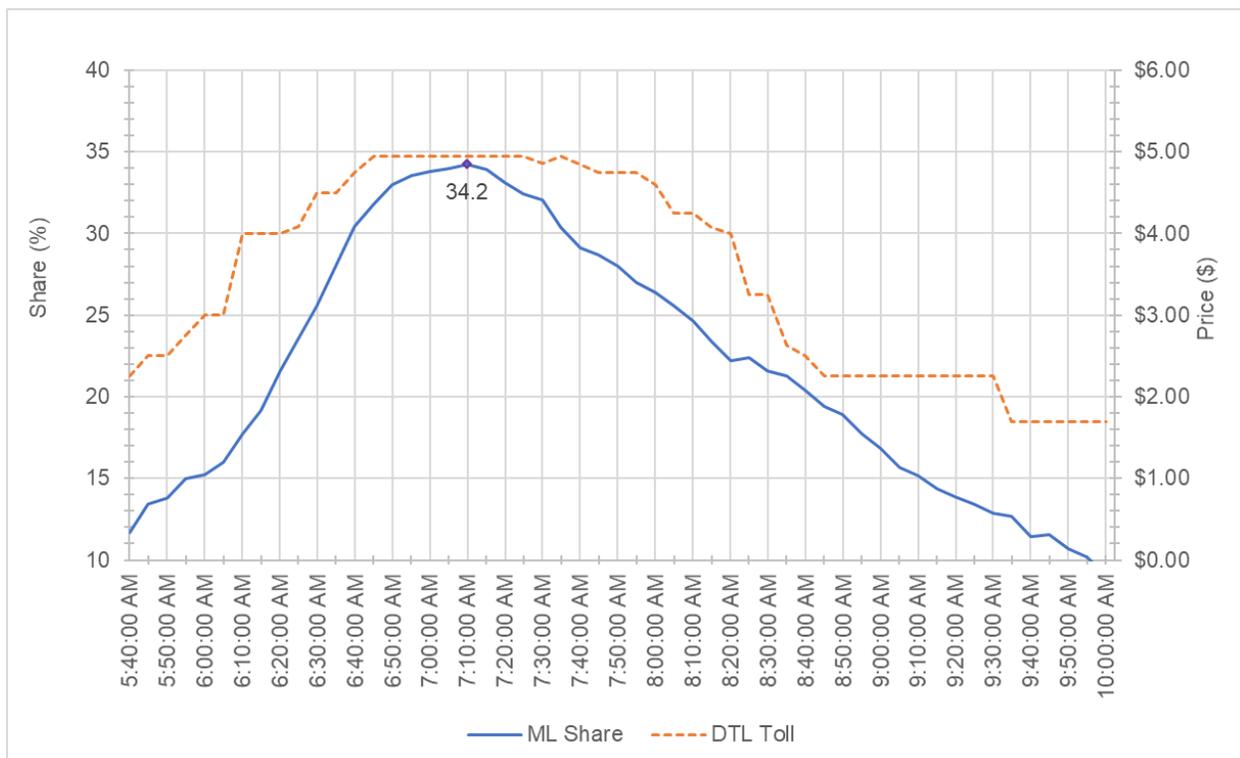


Figure 29 - Weekday DTL traffic share percentage and DTL price for EB direction

Figure 30 shows the average traffic flow and DTL price paid per 5-minute period for the WB direction in the afternoon. In contrast with the EB direction, the location of the WB traffic counts for the GTL at the Toa Baja station, Plaza ID 7, happen almost at the end of the DTL corridor. Therefore, the GTL counts at located approximately at km-marker 22, add or lose traffic from three interchanges after the DTL entry point. The traffic counts from the Buchanan toll station, Plaza ID 18, prior to the DTL entry in km-marker 12, parallel to the Río Hondo Shopping Center, is added as a reference of the potential magnitude of traffic that could be passing at the DTL entry point. There are two interchanges after the Buchanan toll station before reaching the DTL entry point so the comparison with the EB direction will not be clear-cut.

The traffic plot shows behavior that can be considered representative for the afternoon traffic flow on the freeway, although there is less traffic than in the morning, but with a longer peak period. The peak traffic flow for the freeway is observed at around 4:15 p.m. with 320 vehicles for a 5-minute period; that is about a 20% difference compared with the morning peak count. At the peak, the traffic share for the DTL is 15.6% based on the Toa Baja GTL count or 7.6% based on the Buchanan GTL count. The WB traffic peak for the DTL occurs 10 minutes later, with 50 vehicles / 5-min. Proportionally, there is less traffic for the p.m. peak for an 83% difference with the morning DTL peak count. From 2:00 to 4:20 p.m. the traffic using the DTL gradually increases, but at a different rate than in the morning, with traffic considerably steady for the Toa Baja GTL counts. In the case of the Buchanan GTL counts, traffic behaves less uniformly, but still with an increasing trend until 4:15 p.m. As traffic on the DTL increases, the toll paid for the use of the DTL also increases, as expected, but the pattern is different than for the morning period. The peak DTL price reached is about \$3.50. On average, the maximum DTL price of \$4.95 is not reached. After the peak moment, traffic on the DTL steadily decreases for the duration of the afternoon period. Traffic in the afternoon is more dispersed than during the morning peak. The pricing algorithm takes about 210 minutes to reach the maximum toll value when traffic is increasing and about 135 minutes to change from the maximum to the minimum value when traffic is decreasing.

Figure 31 shows the traffic share percentage for the DTL against the DTL price paid per 5-minute periods during the afternoon period. Again, the comparison is made with the Toa Baja and Buchanan toll stations, one after and one before the DTL entry point, respectively. The data reflects the increasing trends for both comparisons. As shown in the figure, the highest traffic share for the DTL occurs at about 4:35 p.m. with 16.4% of the traffic on the WB direction for the Toa Baja station and 9.3% for the Buchanan stations. The highest traffic share corresponds to a period when the DTL price has not yet reached its maximum price.

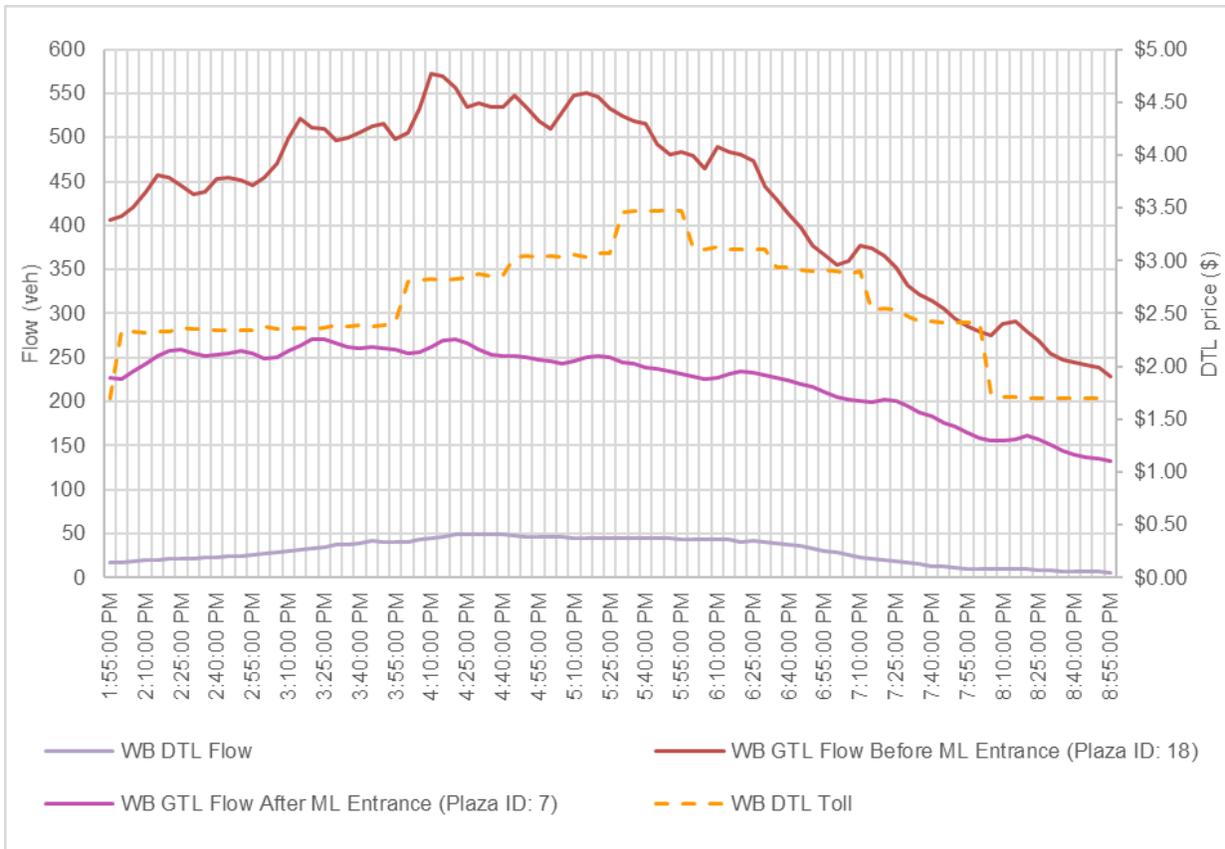


Figure 30 - GTL and DTL traffic flows and DTL price paid for WB direction

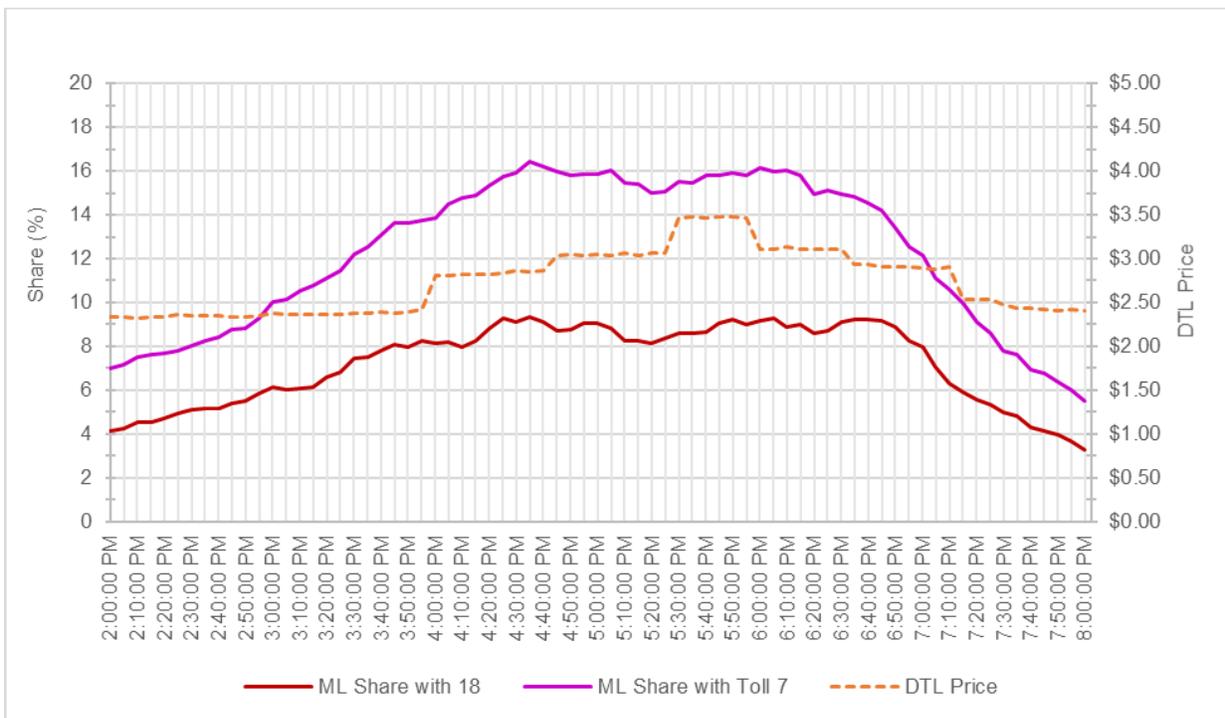


Figure 31 - DTL traffic share percentage and DTL price for WB direction

b. Performance Measures

i. Travel Time Index and Travel Time Savings

The calculation of the Travel Time Index (TTI) was done separately for the two DTL entry points and the GTL. Table 11 presents the TTI results for the two groups of lanes for the total morning and peak traffic periods. The peak travel time was estimated for each lane type and divided by the free-flow travel time (FFTT) to obtain the TTI. The FFTT was estimated by dividing the distance between two consecutive toll stations by the free-flow speed (FFS) of each lane group. The DTL sensors 112 and 113 and the Toa Baja Station are separated by approximately 3,850 feet (1,173 m), therefore the FFTT was estimated according to the distance. Speeds on the DTL for the WB direction were not available so TTI values were not calculated. The FFS was estimated as the average speed at a time when the roadway traffic experiences no congestion or other adverse conditions that can affect travel. For this study, the free-flow period was established from 10 p.m. to 4 a.m. The travel time savings (TTS) was obtained by subtracting the GTL TT value with the DTL TT from the same period.

Table 11 - Total morning and peak period TTI values

(a) DTL 112 Station to Buchanan Station					
Period	Annual Free Flow Speed (mph)	Free Flow Travel Time, FFTT (minutes)	Travel Time, TT (minutes)	Difference TT - FFTT (minutes)	TTI
Total morning	64	7.31	7.79	0.47	1.06
Peak			8.98	1.67	1.23

(b) DTL 113 Station to Buchanan Station					
Period	Annual Free Flow Speed (mph)	Free Flow Travel Time, FFTT (minutes)	Travel Time, TT (minutes)	Difference TT - FFTT (minutes)	TTI
Total morning	64	7.31	7.95	0.64	1.09
Peak			8.97	1.66	1.23

(c) GTL Toa Baja Station to Buchanan Station					
Period	Annual Free Flow Speed (mph)	Free Flow Travel Time, FFTT (minutes)	Travel Time, TT (minutes)	Difference TT - FFTT (minutes)	TTI
Total morning	61	6.88	8.37	1.49	1.22
Peak			15.95	9.08	2.32

The TTI results for the DTL sensors 112 and 113 are comparable, therefore the results from sensor 112 will be used for the following discussion. The average travel time (TT) on the GTL for the entire morning period was 8.37 minutes, whereas the DTL users had an average TT of 7.79 minutes. There is a difference of only 0.58 minutes between these two TT values for the morning period. The entire morning period covers from 4:30 a.m. to 12:00 p.m., so it includes the impacts of both peak and non-peak traffic conditions.

The key benefits in travel time savings of the DTL certainly are exhibited during the peak morning period. The average TT in the GTL during the peak period of traffic degrades to 15.95 minutes, for a 131.8% increase when compared with its FFTT. During the peak period, traffic on the DTL also increases, as it was shown in Figure 27, but the related increase in the average TT due to the presence of more traffic in the

DTL is only 6.6%. This result is representative of the impact that the dynamic toll fee has on the drivers' decision of selecting the DTL as a travel option. Certainly, the pricing algorithm is working as desired of not allowing trip quality to degrade as much in the DTL during the peak period.

The difference in TTI values between the GTL and DTL during the peak period also sustains the benefits for the DTL users on the corridor. The TTI for the DTL was calculated as 1.23, whereas the TTI for the GTL was 2.32, for a difference between the two values of 1.09, or 88.6%. Using as an example a trip that has a free-flow travel time of 10 minutes, the TTI for the GTL represents the commuter will have a TT of 23.2 minutes. For the same 10-minute trip, the DTL user would just take 12.3 minutes, for a TT gain of 10.9 minutes.

Recall the TTI value of 1.33 for the SJMA for 2017, as published on the 2019 Urban Mobility Report. Consequently, the PR-22 DTL corridor has a better TT performance compared to the rest of the network in the region. In contrast, the PR-22 GTL is underachieving significantly.

ii. Planning Time Index and Planning Time Benefit

The calculation of the Planning Time Index (PTI) was done also for the total morning and peak traffic periods. Table 12 presents the PTI results for the two DTL entry points and the GTL for the morning operation. The 95th percentile travel time was estimated for each lane type and divided by the FTT to obtain the PTI. The same FTT and FFS estimated for the TTI were used for this calculation. As with the TTI measure, WB speeds on the DTL were not available.

Table 12 - Total morning and peak period PTI values

(a) DTL 112 Station to Buchanan Station					
Period	Annual Free Flow Speed (mph)	Free Flow Travel Time, FTT (minutes)	95 th Percentile Travel Time, 95TT (minutes)	Difference 95TT - FTT (minutes)	PTI
Total morning	64	7.31	11.65	4.34	1.59
Peak			12.25	4.94	1.68

(b) DTL 113 Station to Buchanan Station					
Period	Annual Free Flow Speed (mph)	Free Flow Travel Time, FTT (minutes)	95 th Percentile Travel Time, 95TT (minutes)	Difference 95TT - FTT (minutes)	PTI
Total morning	64	7.31	11.20	3.89	1.53
Peak			12.23	4.92	1.67

(c) GTL Toa Baja Station to Buchanan Station					
Period	Annual Free Flow Speed (mph)	Free Flow Travel Time, FTT (minutes)	95 th Percentile Travel Time, 95TT (minutes)	Difference 95TT - FTT (minutes)	PTI
Total morning	61	6.88	20.17	13.29	2.93
Peak			27.25	20.37	3.96

The difference in PTI measures between the lane types demonstrates the significant benefits in improved travel time reliability attained by the DTL users when selecting the facility. The PTIB is obtained by subtracting the GTL PTI value with the DTL PTI value. As with the TTI, the PTI results for the DTL sensors 112 and 113 are comparable, therefore the results from sensor 112 will be used in the following discussion. The 95th percentile TT on the GTL was 20.17 minutes, whereas the DTL users had 12.25 minutes

in TT on the corridor. These measures alone represent a difference in TT of 7.92 minutes. This TT represents PTI values of 2.93 for the GTL and 1.59 for the DTL, for a PTIB of 1.59. For a trip that has an FTT of 15 minutes, the PTI for the GTL indicates a commuter will have to plan for almost 44 minutes to avoid being late for that trip at least one time in a month. For the same trip, the DTL user would just need to plan for 24 minutes, for a gain of 20 minutes in the planning time of the trip. The difference in PTI values is even higher during the peak traffic period (i.e., 3.96 for the GTL vs. 1.68 for the DTL sensor 112). Using the same 15-minute trip during free-flow, a commuter will need to plan for 59 minutes on the GTL versus approximately 25 minutes on the DTL.

Figure 32 shows the comparison of PTI values per month for the GTL and the two DTL sensors for the EB direction. The PTIB per month is shown with the green line in the graph, expressed in travel time savings for a 15-minute free-flow trip. The data presents the seasonal patterns of traffic congestion along the PR-22 during 2019. As expected, the month of July exhibits the lowest PTI value for all lane types, and thus the lowest benefit in travel time for the year. The worst reliability performance of the GTL occurred in February and September with a PTI of 3.47. When analyzing the travel time savings for the example 15-min. trip, the use of the DTL proved to be most helpful in February with 28 minutes. The worst reliability for the DTL happened in September and October, therefore the benefit of using the DTL was diminished.

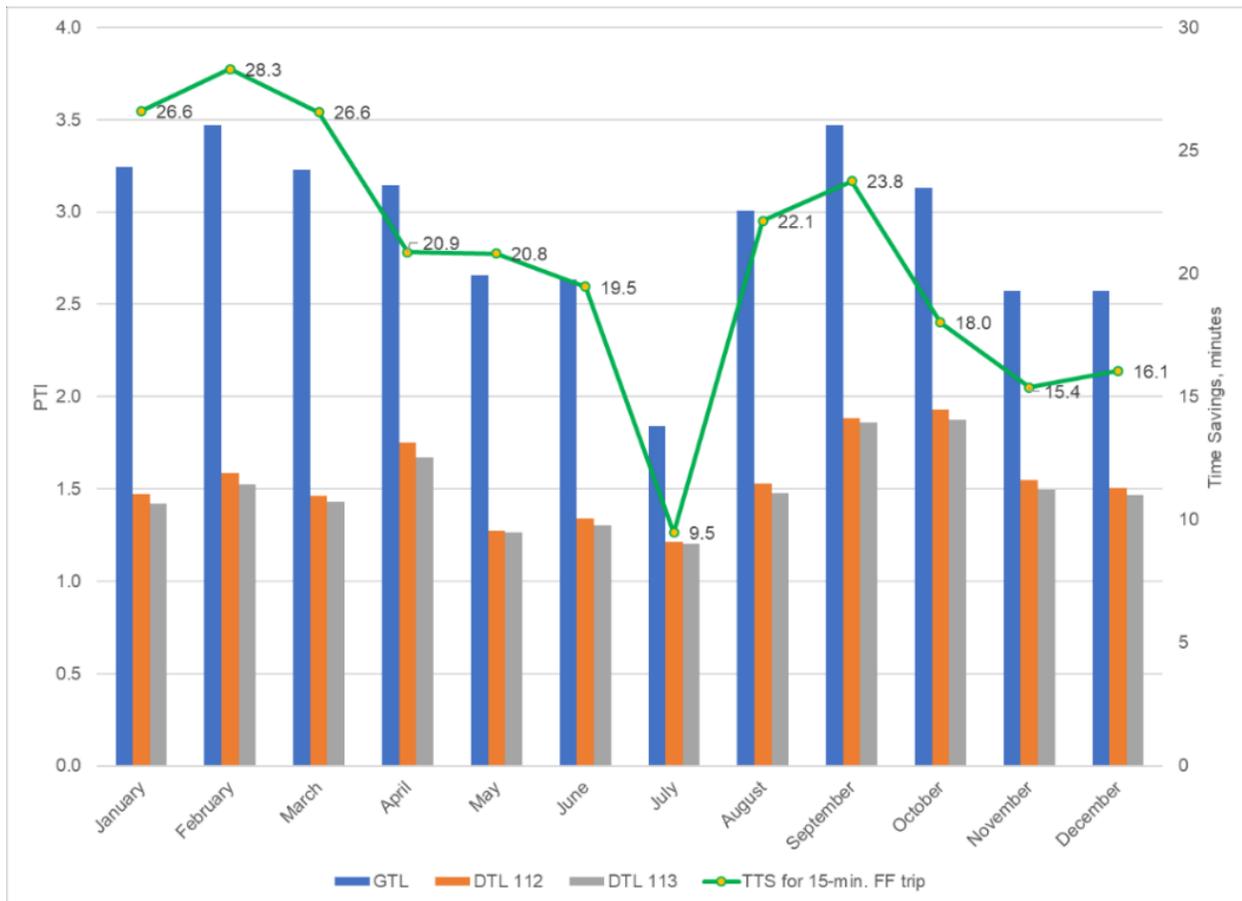


Figure 32 - Comparison of monthly PTI for EB direction

iii. Ability of Toll to Impact Congestion

For the calculation of the Ability of Toll to Impact Congestion (ATIC) measure, the DTL traffic data was grouped into different toll price bins using \$1.00 increments. The calculation was performed separately for the before and after peak periods. The reasoning of dividing the calculation of ATIC into these two periods allows the measure to consider the increasing and decreasing trend of the traffic volumes and toll prices due to the congestion factor in the DTL. The PR-22 DTL has a dynamic pricing scheme as a function of traffic speeds in the median lanes. Table 13 shows the ATIC values for the 2019 data. The ATIC measure demonstrates what is the price range when the DTL is managing traffic entering the facility.

Table 13 - ATIC Results

Period	Price Range (\$)	ATIC a.m. Operations	ATIC p.m. Operations
Increasing Traffic Range	2.00-2.99	1.7	1.4
	3.00-3.99	-1.2	27.6
	4.00-4.99	19.5	-2.5
Decreasing Traffic Range	2.00-2.99	3.6	3.1
	3.00-3.99	-0.8	-0.1
	4.00-4.99	20.9	-3.4

By separating the before and after peak periods, it can be observed when users start taking into consideration choosing the DTL over GTL. During the morning operation, the ATIC results in a negative value for the \$3.00-\$3.99 price for both the increasing and decreasing traffic periods. Note that the maximum limit of the WTP range was estimated as \$2.79 from the VWPSM analysis. Therefore, the \$3.00-\$3.99 represents a DTL price that is over the WTP of the PR-22 users and paying that price does not provide enough utility in a general sense. Once the DTL price reaches the highest range of \$4.00-\$4.99, the ATIC results indicate that drivers see more utility in using the DTL assuming that traffic conditions on the GTL will be worsened. During the afternoon period, the lowest negative values for the ATIC were observed for the \$4.00-\$4.99. In other words, the negative ATIC value shows when the DTL price starts excluding users by their WTP which is in function of their income, age, gender, and other factors. These trends in ATIC values are comparable to those obtained from Burriss et al. [2021]. The negative ATIC values in the table represent when the pricing mechanism is in control of the vehicle throughput to avoid degraded conditions in the DTL.

iv. Speed Threshold

The Speed Threshold (ST) measure was calculated for the morning operations of the PR-22 DTL. The criterion for identifying good performance, as recommended by the FHWA, is that the traffic on the facility must maintain a minimum average operating speed 90 percent of the time over a consecutive 180-day period. This measure was established for evaluating the performance of HOV facilities, but the metric is also recommended for application to other managed lanes [FHWA, 2006]. For this study, the analysis was first done using the 45-mph speed threshold, even though the DTL has a posted speed limit of 45 mph. A second check was performed using the 35-mph speed threshold, which follows the standards established in USC 23 Section 166(d)(2)(A). The graphical results using the 35-mph threshold are shown in Appendix D. The underlying assumption is that using the 35-mph limit as the ST will result in a better performance for the DTL than for the 45-mph speed limit. The posted speed limit on the GTL is 55 mph, which makes for a clashing situation with the lower speed limit and the intended purpose of improved travel times for

the DTL. The decision to set a 45-mph speed limit on the DTL was primarily based on safety concerns for the geometry at the west end of the facility and the clear zone availability inside the facility.

The ST was analyzed using data from 5-minute intervals for the DTL peak hour and the morning period in the EB direction. Table 14 presents the results for the ST analysis. The PR-22 DTL meets the 35-mph threshold for 95.8% of the peak period. In contrast, when applying the 45-mph threshold, the DTL performs at or above the threshold only 81.6% of the analysis period. The application of this measure on the PR-22 DTL requires further study. Recall that the free-flow speed on the DTL was estimated at 64 mph. Also, recall that the speeds used in this study are not from spot-speed measurements and are an approximation based on vehicles that passed through two consecutive toll stations.

Table 14 - Speed Threshold for the DTL EB direction

Period	Speed Threshold (ST)	Percentage of time > ST	Number of days meeting threshold
Morning: 5:00 -11:00 a.m.	35	98.8	240
	45	94.4	195
Peak: 6:40 - 7:35 a.m.	35	95.8	222
	45	81.6	163

Figure 33 shows a visualization analysis to compare average speeds from the GTL and DTL. The graph includes the speed database generated for the year 2019 with each point representing a 5-minute interval. The color gradient represents quintile groups generated based on the number of points surrounding each observation. The visualization allows for an easier representation of the average speed performance and comparison between lane types on the facility. The horizontal and vertical lines represent the speed threshold based on the 45-mph limit and the diagonal line at a 45-degree angle serves to identify when the DTL over or underperforms relative to the GTL. The boxes include the percentage of data points in each quadrant or quadrant section.

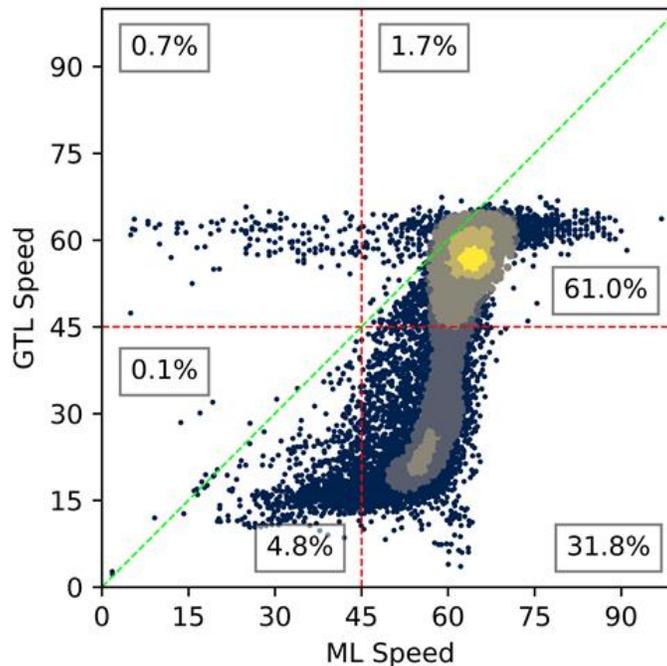


Figure 33 - Speed-Quadrant plot for DTL and GTL

The vertical line set at 45 mph serves to identify the percentage of data points that the DTL underperforms under the ST measure. Using the data in the figure as an example, 5.6% of the time the DTL performed at speeds below the 45-mph limit. The horizontal line does the same for the GTL. In this example, the average speed on the GTL underperforms 79.9% of the time. The diagonal line establishes the direct comparison between the GTL and DTL. Data points over the diagonal line show the period when the DTL speeds are lower than the speeds on the GTL, which presents an unwanted operational condition for the DTL. In this example, that situation happened 2.5% of the time during 2019.

Figure 34 shows the average speed graphs for the DTL and GTL per month in 2019. These visualizations serve to identify seasonal variations of the ST measure. Consistent with the monthly PTI results, the average speed performance on the DTL does not meet the 45-mph ST criterion for September and October. During those two months, the traffic on the DTL exhibits average speeds under 45-mph for 13.3 and 12.7% of the time, respectively.



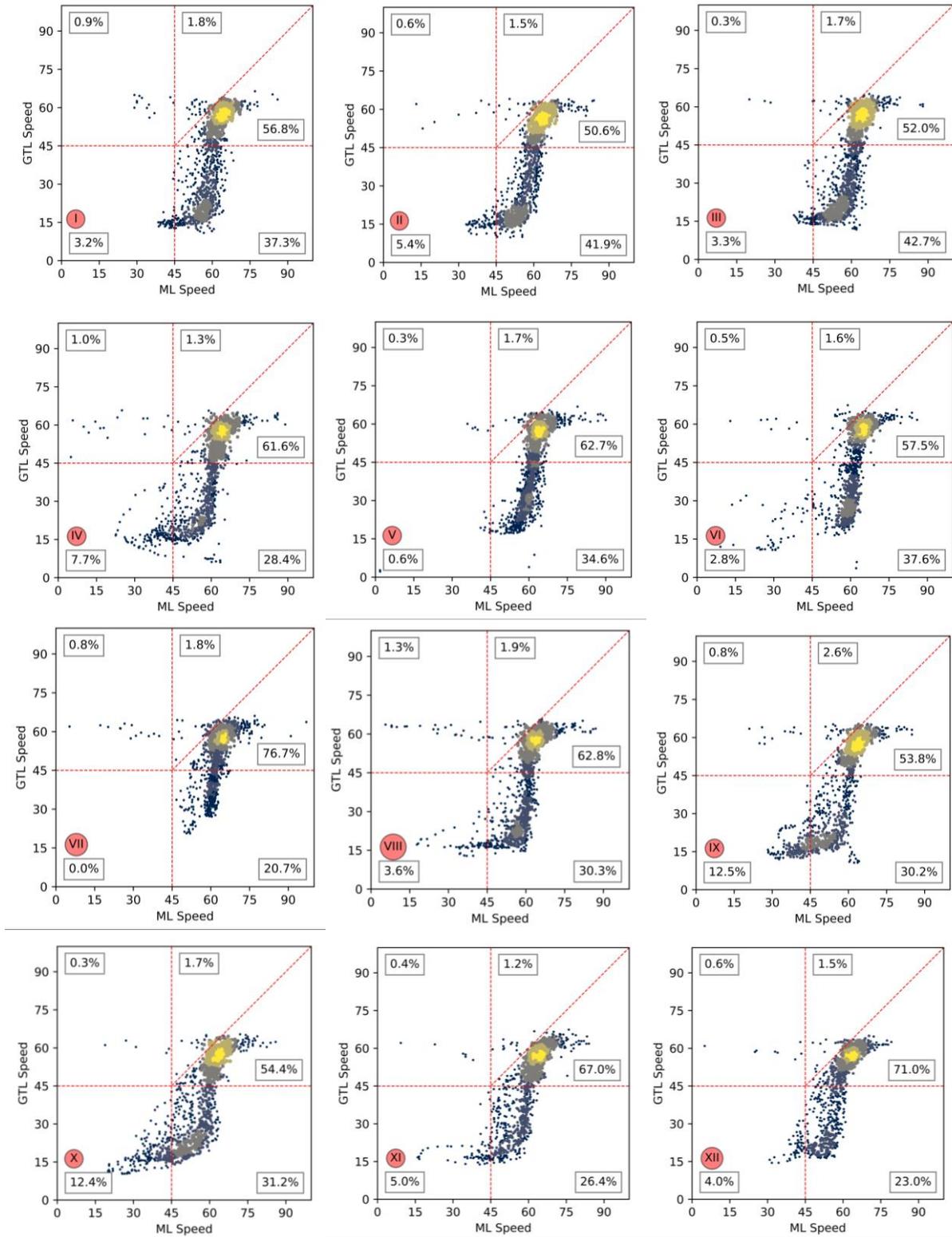


Figure 34 - Speed-Quadrant plots per month for DTL and GTL

v. Dominance Indicators

The results of the D_H -based performance analysis are presented in Figure 35. Time periods consisted of 5-minute periods from 5:00 to 10:30 a.m. for all days in the year with standard operations in the DTL (e.g., on holidays the facility has non-standard operations). The speed scaling factor was 80 mph and the flow scaling factor for each lane type was the maximum observed flow.

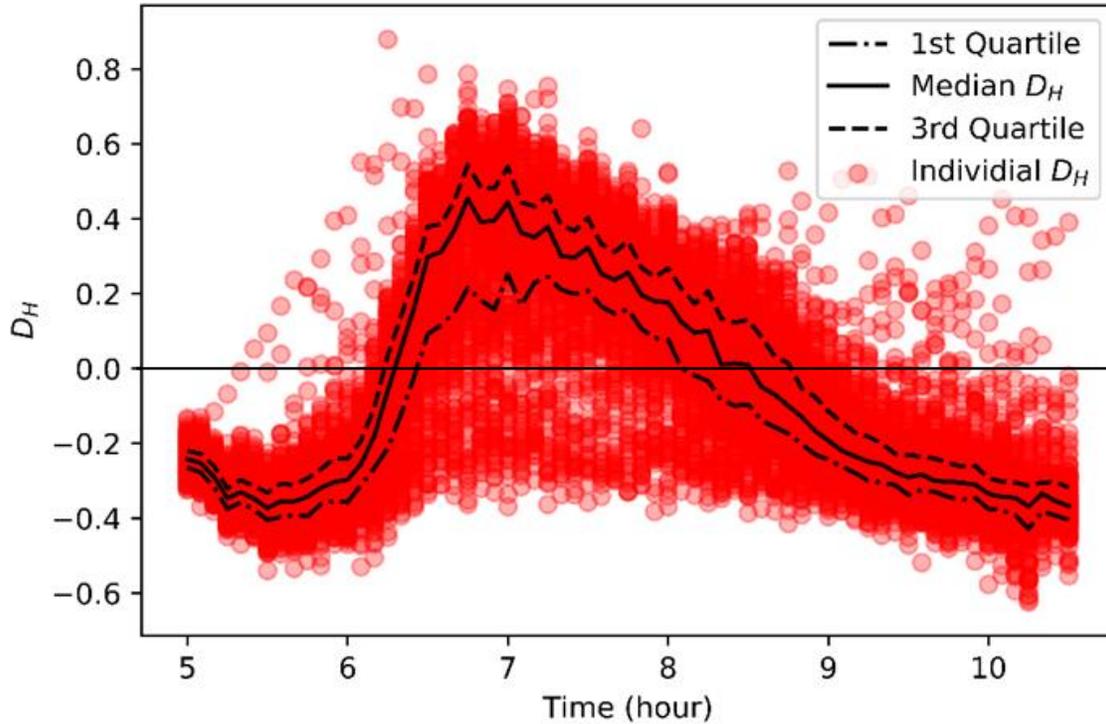


Figure 35 - D_H values during the morning period of operation

The D_H values of all individual t analysis periods are plotted, along with the median, first quartiles, and third quartile values. As it can be observed from the graph, the values of D_H in off-peak periods are negative, while the values are positive during the morning peak period. The off-peak values of D_H can be explained by the relatively low flows in the DTL, coupled with relatively high speeds and flows in the GTL. The peak period values of the D_H can primarily be explained by the markedly higher speeds in the DTL relative to the GTL. Overall periods shown in the figure, the average D_H is -0.06, but in the peak period, the average value is approximately 0.15.

The binary dominance indicator D_b had a value of 26.7, meaning that there were around 27 times more periods in which the DTL operations dominated the GTL operations, but this value is related to the 20% of periods in which the operations of one lane type dominated the operations of another lane type. In 80% of the periods the lane operations are in non-dominated states (e.g., DTL has higher speeds than GTL, but with a lower scaled flow).

The D_S values of all individual t analysis periods are plotted in Figure 36. The u^* value in this analysis was set to 45 mph. In contrast to the pattern observed in Figure 35, two distinct horizontal clusters of points can be observed. This pattern is a product of the sign switch that the $s_{GTL,t}$ terms of the GTL suffer when the traffic speed is less than u^* . As expected, given the results obtained in the speed quadrant graphs, the D_S provides a stronger signal of the better performance of the DTL relative to GTL. The average D_S is 0.30 for the analysis period, but it is 0.84 if only peak period data is considered.

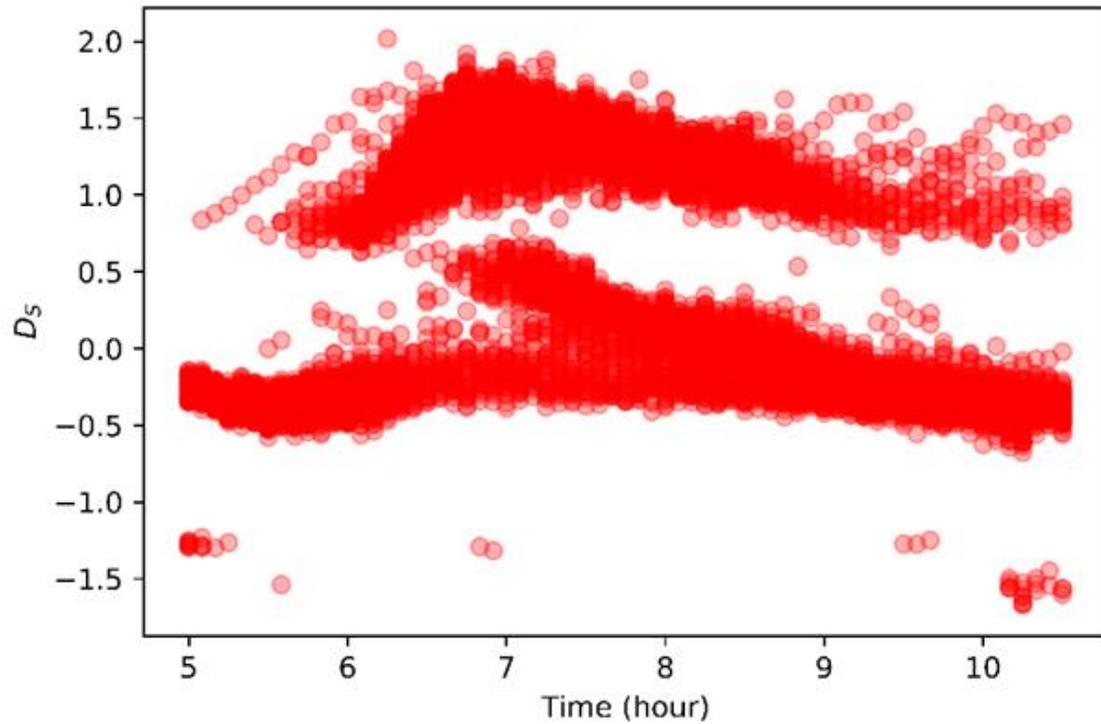


Figure 36 - D_5 values during the morning period of operation

7. Conclusions and Recommendations

The implementation of managed lanes is an innovative active traffic management strategy that has become a preferred countermeasure to effectively tackle congestion on freeway corridors. This report presents the results from a performance assessment conducted of the dynamic toll lanes (DTL) of freeway PR-22 in Puerto Rico. The DTL has a reversible operation with two median lanes along a 7.7-mile-long corridor. The express lanes have a dynamic pricing mechanism with a range of prices between \$1.70 to \$4.95, that change prices based on the real-time speeds. The PR-22 DTL, which started operations in 2013, is the first express lane facility of its kind on a freeway in Puerto Rico.

The main objectives of the study were to calculate performance measures to assess the effectiveness of the pricing mechanism of the DTL, estimate the willingness-to-pay for the freeway users, and estimate the elasticity and value of time from the use of the facility. An online survey with 518 participants and a PR-22 toll transaction database for the year 2019, with over 18 million transactions, were the data sources for this study.

The main results from the online survey of freeway PR-22 users indicate that:

- About 25% of the freeway users choose the DTL at least once a week. These users stated that the COVID-19 pandemic had a significant reduction of at least 67% in their frequency of use of the DTL.
- The most important factors when making the decision to select the DTL are the level of congestion on the General Toll Lanes (GTL), the expected travel time savings, and the trip urgency.
- About 95% of the freeway users surveyed stated to have a positive or neutral opinion about the utility provided by the DTL. Even so, almost two thirds of the freeway users believe the DTL is a reliable option for shorter travel times along PR-22. The TTI and PTI performance measures, calculated using the toll transaction data, confirm this assessment of higher benefits in travel time savings and trip reliability when using the DTL in comparison to the GTL proving the importance of this
- An issue for the DTL facility is the disagreement of freeway users with the level of “good value” that the facility provides for its price. Half the sample judged that the DTL does not provide a good value, while one-third of the sample stated the opposite that it does provide a “good value” for its use. The range estimated for the willingness-to-pay (WTP) for the DTL was from \$1.00 to \$2.79, which is below the maximum price of \$4.95 for the DTL (especially during peak periods) and could deter some freeway users to pay that additional surcharge. The socio-demographic factors found from the survey that reduce the WTP of the freeway users include higher income levels, higher age, and females.
- The Stated Preference model estimated a value of time of \$21.47 per hour for the freeway users. The two factors found to positively affect the decision of using the DTL include the travel time savings and stated DTL users. On the other hand, the factors that negatively affect the selection of the DTL include the toll charged, the age of the subject, subjects in the middle- and high-income levels, and males.

Seven performance measures were calculated from the 2019 toll transaction data for freeway PR-22. The main conclusions from the analyses performed are:

- There is a higher usage of the DTL during the morning period than during the afternoon. The peak periods of traffic on the PR-22 DTL were from 6:35 to 7:35 a.m. in the eastbound direction and from 4:10 to 5:05 pm in the westbound direction. On average, the traffic that uses the DTL was estimated as 999 vph during the morning peak and 573 vph during the

afternoon peak. Correspondingly, the share of traffic using the DTL reaches a maximum of 34.2% during the morning peak and 16.4% during the afternoon peak.

- The pricing algorithm behaves as expected, increasing the price for the DTL as vehicle speeds decrease on the median lanes. The lowest average speed on the DTL was 50 mph at about 7:10 a.m. when the average speed on the GTL was approximately 25 mph.
- Travel Time Savings: The average reduction in travel time for the users of the DTL is approximately 7 minutes for the a.m. peak period. The DTL has a TTI value of 1.23 during the a.m. peak period, in contrast to a TTI of 2.32 for the GTL.
- Planning Time Index Benefit: The Planning Time Index validated the DTL provides benefits in improved travel time reliability when compared with the GTL. Based only on the difference between the 95th percentile travel times for the two-lane groups, the DTL provides a benefit of almost 8 minutes in travel time on the corridor. Using a representative 15-minute trip during free flow, a commuter selecting the DTL to make a trip will gain 34 minutes of travel time, on average, in planning to avoid being late at least one time a month.
- Ability of Toll to Impact Congestion: The ATIC for the DTL resulted in negative values for the \$3.00-\$3.99 price bin for both the increasing and decreasing traffic periods. The negative ATIC values for the price range of \$3.00-\$3.99 demonstrate that the freeway users are less inclined to pay for the DTL at that price range when perceiving that the traffic conditions on the GTL do not merit paying the extra cost versus the expected benefit in the reduction of travel time in the corridor.
- Speed Threshold: The DTL meets the speed threshold by maintaining average speeds over 35 mph for 95.8% for the a.m. peak period and 222 days during the year 2019. The current posted speed limit in the DTL corridor is not consistent with the vehicle speeds on the DTL and GTL in the freeway corridor. The average speeds estimated for the eastbound direction hint at a speeding problem inside the median lanes.

Table 15 presents a summary of the TTS, PTIB, ATIC, and ST results as reported in Burriss et al [2021] from six managed lanes in the United States and the PR-22 DTL from this study. The performance measures shows that the PR-22 DTL provides the highest benefit for its users when comparing the TTS and PTIB values from the other six managed lane facilities. Burriss et al. [2021] indicate that the dynamic priced facilities have a slighter better performance than the variable pricing facilities. The results from the PR-22 DTL are supporting that claim. Nevertheless, the differences found by Burriss et al. [2021] were minimal between the two pricing mechanisms. The authors concur with the main conclusion established in Burriss et al. [2021] that further study and data from additional managed lane facilities are needed to reach a robust inference to determine if one pricing mechanism outperforms the other. A detailed analysis could be made to evaluate if applying a variable pricing mechanism in the PR-22 will achieve the same or better performance results than the dynamic pricing. Nonetheless, the results from the PR-22 DTL demonstrate the dynamic pricing mechanism is providing satisfactory performance for the conditions at the freeway facility.

Table 15 - Summary of performance measures for managed lanes

Measure	Variable Pricing		Dynamic Pricing				
	CA SR-91 Orange Co.	I-25 North Express Lanes	I-35W	I-394	I-35E	MoPac	PR-22 DTL
TTS	0.45	2.56	1.44	2.74	1.03	1.68	6.98
PTIB	0.11	0.56	0.34	0.44	0.36	0.51	2.29
ATIC	Positive values at all prices. Very small (0.04) at max price.	Small negative / positive at higher prices. Large positive at lower prices.	Small positive numbers at higher prices.	Small negative numbers at higher prices	Large negative numbers at higher prices.	Small positive at lower prices. Slightly larger positive / negative at highest prices.	Positive at lower prices. Higher positive values at higher prices. Negative at mid-prices.
ST	No (82%)	Yes (91.9%)	Yes (97%)	Yes (99%)	Yes (100%)	Yes (94.3%)	Yes (95.8%)

The following recommendations to improve the performance of the DTL and to conduct future research studies are offered:

- PR-22 users tend to rely on travel time information from trip planning applications and their understanding of the logic of how the dynamic price mechanism works to use the DTL. Providing additional information to the freeway users, via roadway signs and other information outlets, about the immediate travel time benefits of using the DTL or the added trip time of staying on the regular lanes, have the potential of increasing the usage of the managed lane, particularly from those who are not frequent users or tourists. A simulation study could be conducted to estimate the effect of DTL usage on providing additional information to users. The study could analyze which information strategy and what locations and repetition of the message before the entry point of the managed lanes will work best and determine a benefit-cost of implementing the strategy.
- Freeway users can improve their trip planning and driving behavior when relevant and pertinent information about the existing and future performance level of the freeway system is provided to them. A dashboard with current and “real-time” information about the traffic conditions and the performance of the DTL and GTL along the PR-22 corridor should be developed and available thru the Internet or a smartphone application. The dashboard could be integrated into existing trip planning applications to increase the amount of pertinent information to users of the DTL.
- An engineering study of the vehicle speeds and the safety record of the DTL facility, since its opening in 2013, should be conducted to determine if a change in the posted speed limit on the facility is justified to improve travel times and reduce the inconsistency of vehicles speeds selected by users of the facility.
- HOV policies are not currently used in the freeway network in Puerto Rico. Equity issues from tolling freeway facilities are typically raised from population groups and frequent users of the GTL that cannot manage to pay the extra fee to use the managed lanes. A simulation study could be developed to analyze the potential impact that implementing a HOV policy for the DTL will have on the person-carrying capacity, the performance metrics, congestion reduction, vehicle emissions, and revenue on PR-22. The study could analyze what the minimum vehicle occupancy level should be and could also evaluate different pricing schemes with reduced tolls or no fee for HOV vehicles and identify possible implementation challenges and opportunities.
- A new reversible DTL facility was inaugurated in April 2021 on a corridor that goes through the median of freeways PR-52 and PR-18. This new facility also has a dynamic pricing mechanism, but with various entry and exit points. A similar study to assess the performance

of the new facility can be conducted to establish strategies to improve the usage of the facility and reduce the congestion in the corridor.

- A forthcoming study from NICR, by the Texas A&M University and the University of Puerto Rico at Mayaguez, will analyze the effects of the COVID-19 pandemic on travel, using the PR-22 toll transaction data and other sources. It will also estimate post-pandemic travel trends to identify potential strategies to build back the ridership of transportation services. Freeway PR-22 data from the second part of 2020, and from the first six months of 2021, can be provided to the UPRM team to expand the analysis of the during pandemic period and study the impacts of the changes made to health and safety rules established by the federal and territory governments.



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APPENDICES

Appendix A: Survey Welcome Message and Introduction



Encuesta sobre uso del Carril Expreso (DTL)
de la Autopista José de Diego (PR-22)

Encuesta sobre el Carril Expreso de la Autopista PR-22 José de Diego

*Obligatorio

Información sobre el Carril Expreso de la Autopista PR-22 José De Diego

Muchas gracias por aceptar participar en nuestra encuesta.

El carril expreso de la Autopista José de Diego (PR-22), también conocido como carril reversible, carril de peaje dinámico o "dynamic toll lane" (DTL), se localiza a lo largo del medio de la carretera entre los carriles regulares entre los municipios de Toa Baja y Bayamón. El carril expreso es reversible, permitiendo el tráfico en dirección hacia San Juan durante las mañanas y luego permitiendo el tráfico en dirección hacia Vega Baja/Manatí durante las tardes. El peaje del carril expreso es una tarifa variable adicional al peaje regular basado en las condiciones reales de tráfico en la autopista. Las siguientes imágenes muestran el tramo y señalización del carril expreso de la Autopista PR-22.



Appendix B: UPRM IRB Approval of Survey Instrument and Protocol

	Institutional Review Board CPSHI/IRB 00002053 University of Puerto Rico – Mayagüez Campus Dean of Academic Affairs Call Box 9000 Mayagüez, PR 00681-9000	
<h3 style="margin: 0;">Protocol Approval</h3>		
Approval Date	October 7, 2020	
Protocol Number	2020090012	
Protocol Title	Pricing Mechanisms for Managed Lanes	
Main Researcher	Dr. Alberto M. Figueroa Medina	
Type of Review	Project Request	
Approval	Expedited	
Category(ies)	7	
Exemption Request(s)	Exemption of use of adult consent for research with minors form Exemption of collection of signature (online research)	
Expiration Date	October 6, 2021	

Any modifications or amendments to the approved protocol or its methodology must be reviewed and approved by the IRB before they are implemented, except in cases where the change is necessary to reduce or eliminate a potential risk for participants. The IRB must be informed immediately if an adverse event or unexpected problem arises related to the risk to human subjects. The IRB must also be notified immediately if there is any complaint about the research or if a breach of confidentiality has occurred.



Dr. Pedro M. Vásquez Urbano
Associate Dean of Academic Affairs

CPSHI / IRB - RUM
No. 00002053
APPROVED

Telephone: (787) 832 - 4040 x 6277, 3807, 3808 – **Fax:** (787) 831-2085 – **Webpage:** www.uprm.edu/cpshi
Email: cpshirum@uprm.edu

Appendix C: AADT Tables per PR-22 Toll Station

Table C1 - 2019 MADT and AADT for Hatillo Toll Stations 1 and 11

		MADT (vpd)												
Month	DOW	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	2019
	Mon	33,492	34,381	34,757	35,441	33,663	34,582	33,354	34,083	33,215	33,391	34,727	37,237	34,360
	Tue	32,517	34,862	34,686	34,916	34,467	34,284	33,909	34,838	29,042	34,005	34,832	34,040	33,866
	Wed	35,213	35,801	35,911	36,662	35,307	35,704	35,976	29,687	33,724	34,711	36,947	33,728	34,947
	Thu	35,460	36,502	36,772	37,541	36,333	36,406	32,869	35,448	35,681	35,540	33,846	37,444	35,820
	Fri	39,120	40,524	40,221	35,209	39,674	40,096	37,855	39,708	39,214	39,341	39,783	40,431	39,265
	Sat	35,070	34,574	36,614	36,633	36,751	35,846	34,714	35,812	34,656	35,511	35,201	36,286	35,639
	Sun	29,289	31,020	32,555	31,120	31,476	31,443	31,739	30,993	29,653	30,970	30,960	32,074	31,108
													AADT (vpd)	35,001

Table C2 - 2019 MADT and AADT for Arcibo Toll Stations 3 and 4

		MADT (vpd)												
Month	DOW	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	2019
	Mon	44618	47343	48669	48366	45905	48249	45217	47740	46262	47209	48082	50012	47306
	Tue	45267	48856	47636	48904	48540	48927	47025	48999	41521	49181	48446	46675	47498
	Wed	48420	49880	51341	50878	49278	50269	49692	41349	47815	50071	51606	47823	49035
	Thu	49071	51382	53089	50893	50599	50843	44233	49249	51047	50923	48057	51682	50089
	Fri	51815	54373	55087	47700	53302	54894	49871	53967	53598	54226	52627	54605	53005
	Sat	42803	44343	45697	44677	45108	44746	42754	44417	43773	45180	43702	47183	44532
	Sun	38673	39549	41875	40801	41080	40796	40516	39295	38251	40169	40087	41829	40243
													AADT (vpd)	47,387

Table C3 - 2019 MADT and AADT for Manatí Toll Stations 5 and 15

		MADT (vpd)												
Month	DOW	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	2019
	Mon	53257	55515	57134	56630	53866	56854	53920	56230	54395	55278	55988	58908	55665
	Tue	54119	57720	58613	57828	57686	58499	56849	58483	48774	57284	57479	56146	56623
	Wed	56989	58948	59667	59888	58717	59569	59756	49379	56329	58597	60690	56869	57950
	Thu	58246	60133	61990	60074	60245	59836	53962	58715	60147	59581	56812	61240	59248
	Fri	61647	64169	65052	56547	63760	65035	59773	64176	63729	64047	62474	65168	62965
	Sat	52565	53968	54996	53355	54431	54383	52080	54013	53317	54788	53564	59067	54210
	Sun	47964	47940	50706	48479	49786	49121	49095	47783	46254	48373	48738	51858	48841
													AADT (vpd)	56,500

Table C4 - 2019 MADT and AADT for Vega Alta Toll Stations 6 and 16

		MADT (vpd)											
Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	2019
Mon	67146	67342	70135	70436	67640	71429	67402	70552	67664	68712	70673	73966	69425
Tue	67763	68896	72039	72094	72133	73483	71534	72559	61079	71224	72299	70230	70444
Wed	71221	71158	73389	74441	73045	74560	74829	62209	70020	72893	75440	71489	72058
Thu	72905	72875	75793	74343	74910	74718	68206	73500	74573	74177	71285	76530	73651
Fri	76467	76824	79156	69933	78733	80265	74947	79587	79131	79158	77795	80978	77748
Sat	63521	62561	66312	68120	67676	68803	65979	68819	68300	69700	68847	75058	67808
Sun	58546	56782	61256	60808	62264	61896	60765	59939	58646	60979	61587	63805	60606
AADT (vpd)													70,249

Table C5 - 2019 MADT and AADT for Toa Baja Toll Stations 7 & 17 & DTL Stations 111, 112 and 113

		MADT (vpd)											
Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	2019
Mon	96697	99135	101472	100565	96849	99321	92662	99066	94417	96513	99607	104444	98396
Tue	96025	102772	103927	103567	103129	103298	99472	102666	87225	101004	101751	99723	100380
Wed	101728	102358	104237	105851	104091	104864	103389	88762	99486	102603	105425	100447	101937
Thu	104366	106266	109059	105126	106768	105014	92864	103412	104878	104099	98542	108270	104055
Fri	108713	110788	111828	97577	111317	110746	103376	110203	108745	108233	108585	113313	108618
Sat	93424	98766	98972	94987	97474	95345	89538	94766	94010	94136	95556	104568	97671
Sun	78952	79246	84410	79626	83034	80465	77793	78923	77026	79849	80535	86220	81848
AADT (vpd)													98,987

Table C6 - 2019 MADT and AADT for Buchanan Toll Stations 8 and 18

		MADT (vpd)											
Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	2019
Mon	145286	149615	158015	158556	149300	158485	141799	156273	147017	149617	155063	162933	152663
Tue	147738	161268	163485	163578	161841	164032	158450	162058	139025	161068	160597	156733	158323
Wed	158392	161424	165797	164771	161773	167304	163676	138433	158909	163246	166723	154354	160400
Thu	162734	166632	170588	162269	167606	169830	140950	163525	166244	165653	152608	170032	163223
Fri	169596	174331	174734	150232	174951	175028	160583	175017	173844	173395	170587	181048	171112
Sat	135298	139465	142464	137112	142101	138062	127956	137039	139887	142723	140339	152253	139558
Sun	109112	109441	114665	109836	114804	111638	106641	108579	106894	111562	112197	120354	111310
AADT (vpd)													150,941

Appendix D: Speed-Quadrant Plots for the 35-mph Posted Speed Limit

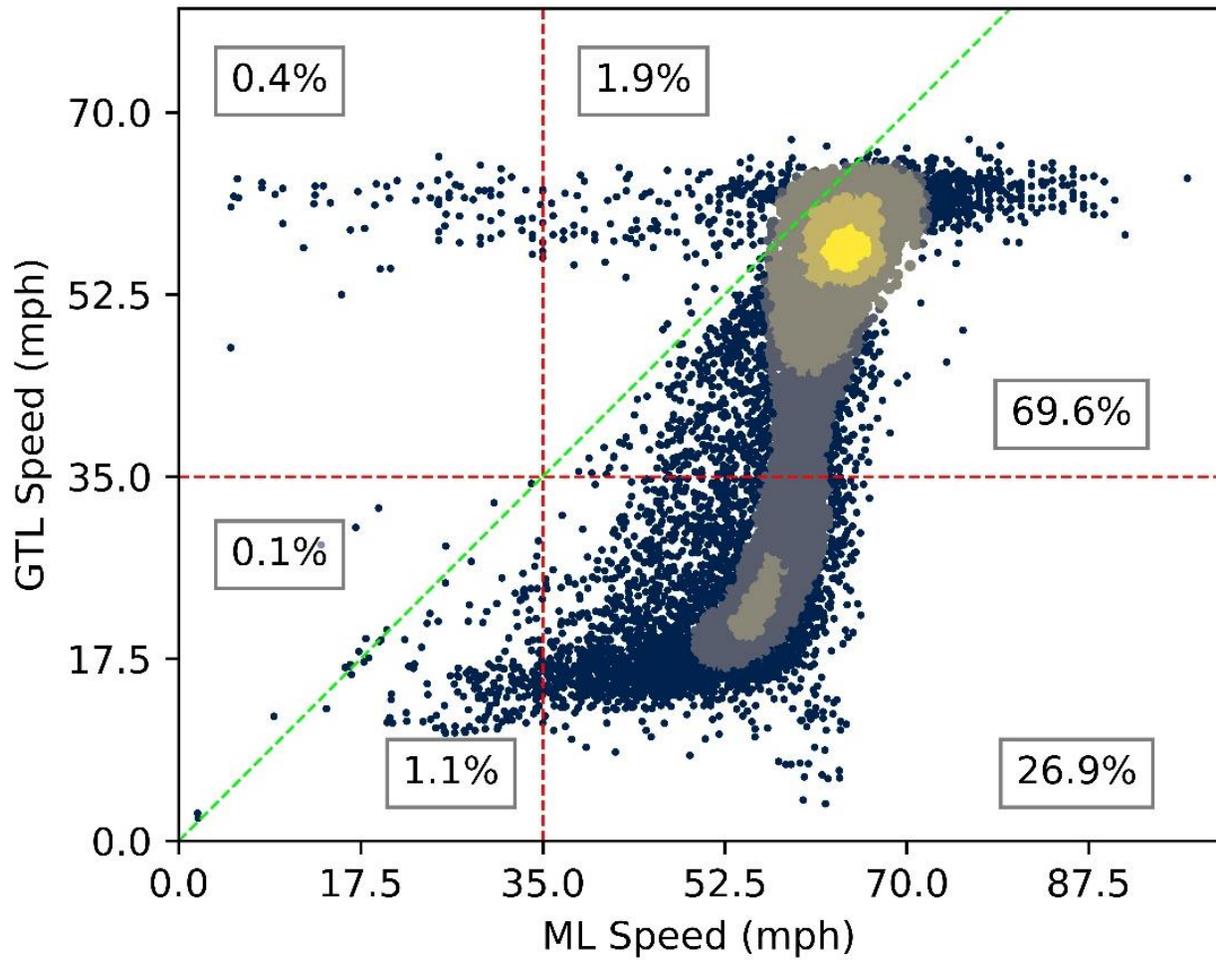


Figure D1 - Speed-Quadrant plot for DTL and GTL based on 35-mph threshold

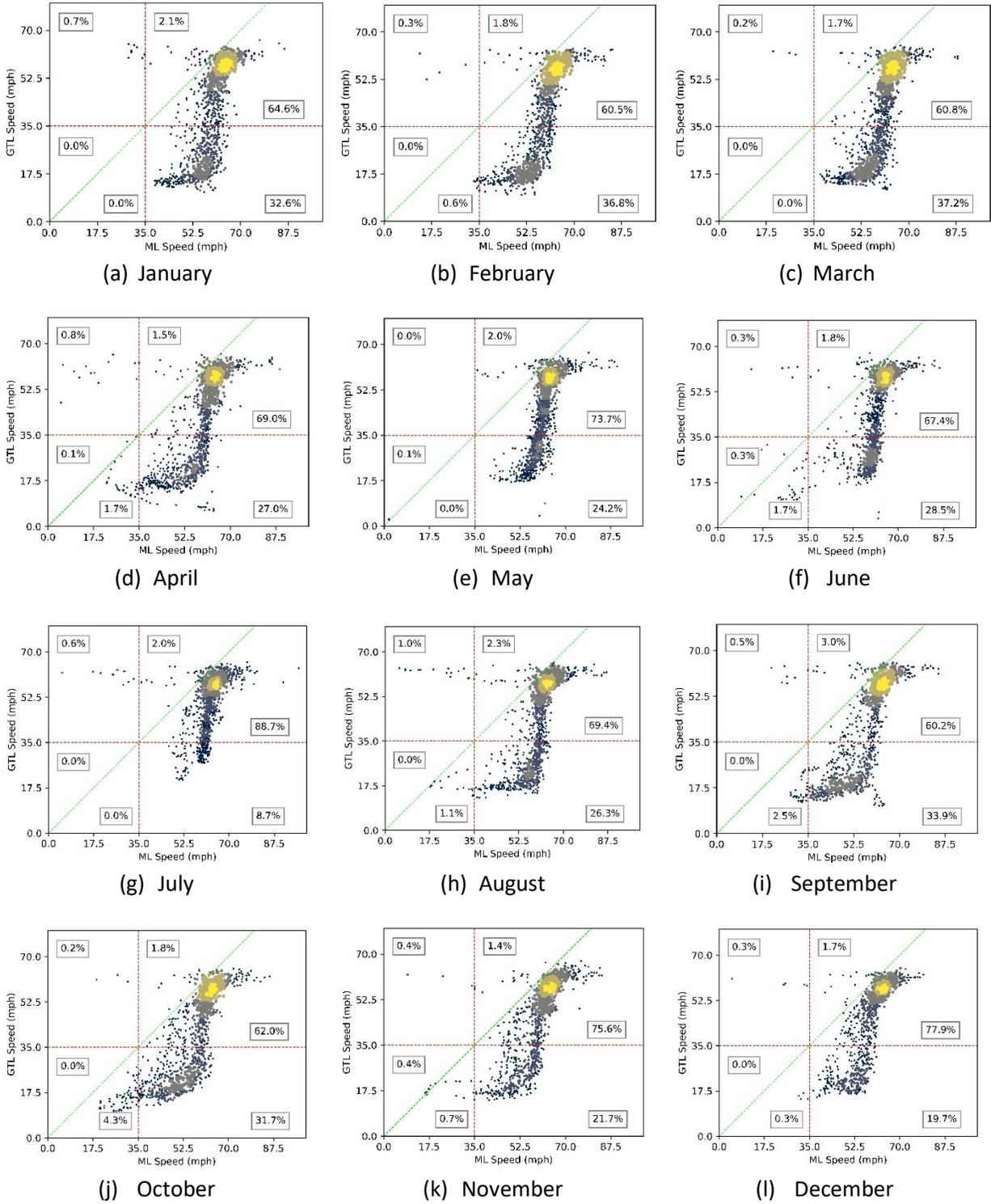


Figure D2- Speed-Quadrant plots per month for DTL and GTL based on 35-mph threshold