Equity Analysis of WSDOT's Toll Program

WA-RD 931.1

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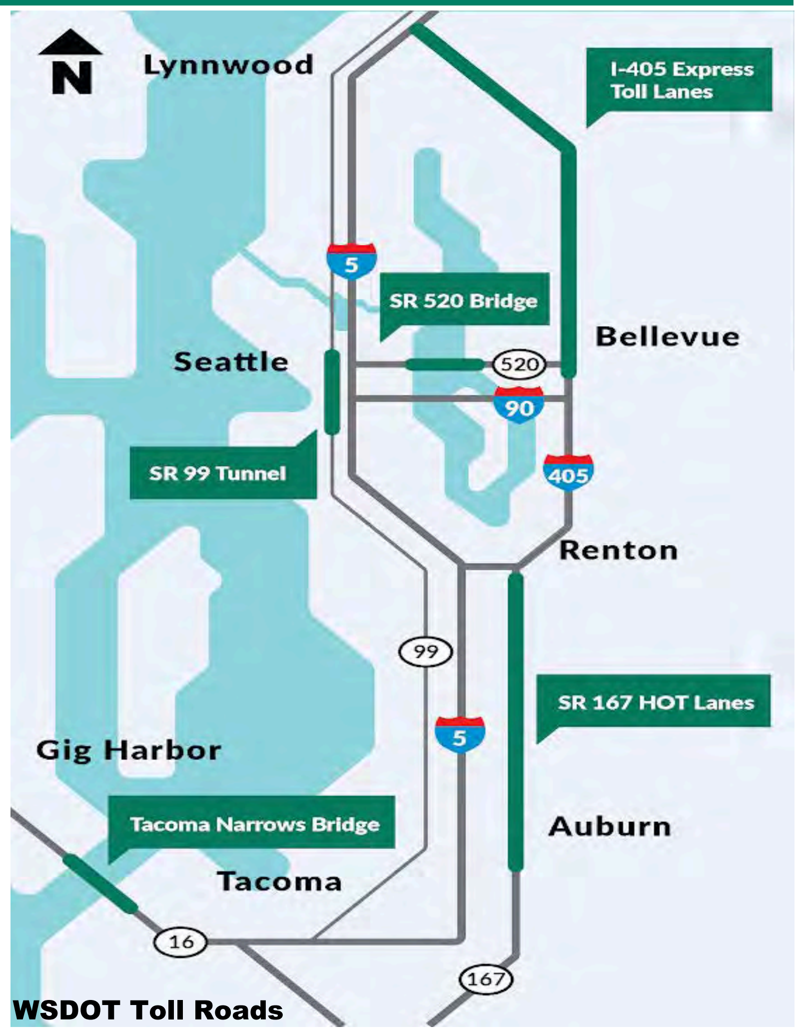
September 2023



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WSDOT Toll Equity
WA-RD 931.1

Equity Analysis of WSDOT's Toll Program

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This study was conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration.

16. ABSTRACT:

The Washington State Department of Transportation (WSDOT) uses tolling to manage highway demand and fund megaprojects. Tolls can raise serious equity concerns, which have been voiced by the Washington State Legislature, the State Transportation Commission, and the WSDOT Secretary. This project aimed to provide insight into the equity of WSDOT's toll facilities, including a literature review of equity analyses that have been performed or that are being considered nationwide.

The project also produced a stand-alone literature review (WSDOT Report WA-RD 931.2) describing income-based toll programs in the United States (U.S.) that are intended to reduce the equity disparities imposed on low-income communities by toll facilities. The literature review also identifies best practices and lessons learned.

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The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Washington State Department of Transportation or Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Executive Summary

INTRODUCTION

The Washington State Department of Transportation (WSDOT) uses tolling as a key mechanism for managing demand on I-405, SR 167, SR 99, and SR 520 and for funding megaprojects such as on SR 16, I-405, projects currently under construction on SR 167, and SR 509. Tolls impose an expense on roadway users, and while tolls are true "user fees," imposition of these fees can create equity concerns.

This project provides insight into the equity of WSDOT's toll facilities. The outcomes from this project will serve as the basis for evaluating the use of the facilities and the implications of that use on the equity of toll facilities. The project was designed to (1) provide WSDOT with a better understanding of the current use of the department's toll facilities; (2) examine how the combination of household income and tolling affect the use of state roadways; (3) provide an understanding of how costs associated with toll facilities are currently being distributed; and 4) provide a baseline of use against which changes in those attributes can be measured given changing economic conditions (e.g., COVID-related changes in overall traffic levels) or policy decisions (e.g., the introduction of a low-income toll program). The project also produced a stand-alone literature review describing income-based toll programs in the United States (U.S.) that are intended to reduce the equity disparities imposed on low-income communities by toll facilities. The literature review also identifies best practices and lessons learned. The literature review is available through the Washington State Transportation Center (TRAC) report website and through the WSDOT library.[1]

The project analyses used data from all five WSDOT toll facilities for the period from July 1, 2021, through June 30, 2022. The analytical results from this project were also compared against similar results for I-405 from 2018, when a study on toll equity was conducted by the University of Washington's (UW) Data Science for Social good (DSSG) program.

[1] The TRAC report website can be accessed here: http://depts.washington.edu/trac/reports/
WSDOT research reports can be obtained by visiting this URL: https://wsdot.wa.gov/about/library-research-reports/research-reports

PROJECT FINDINGS

Who Uses WSDOT's Toll Facilities

Figure ES-1 summarizes the demographic profile of trips made on all five WSDOT toll facilities. It illustrates the number of trips made on each facility by households of each of the primary census income categories. It shows both the volume of toll trips on each facility and the relative income distribution of those trips. Household incomes are estimated on the basis of the census block group to which bills are sent for that account, with commercial accounts (accounts with six or more vehicles) excluded from the income calculations. Figure ES-2 shows this same distribution but normalized by the total number of trips made on each facility to compare the relative number of trips made by each income category.

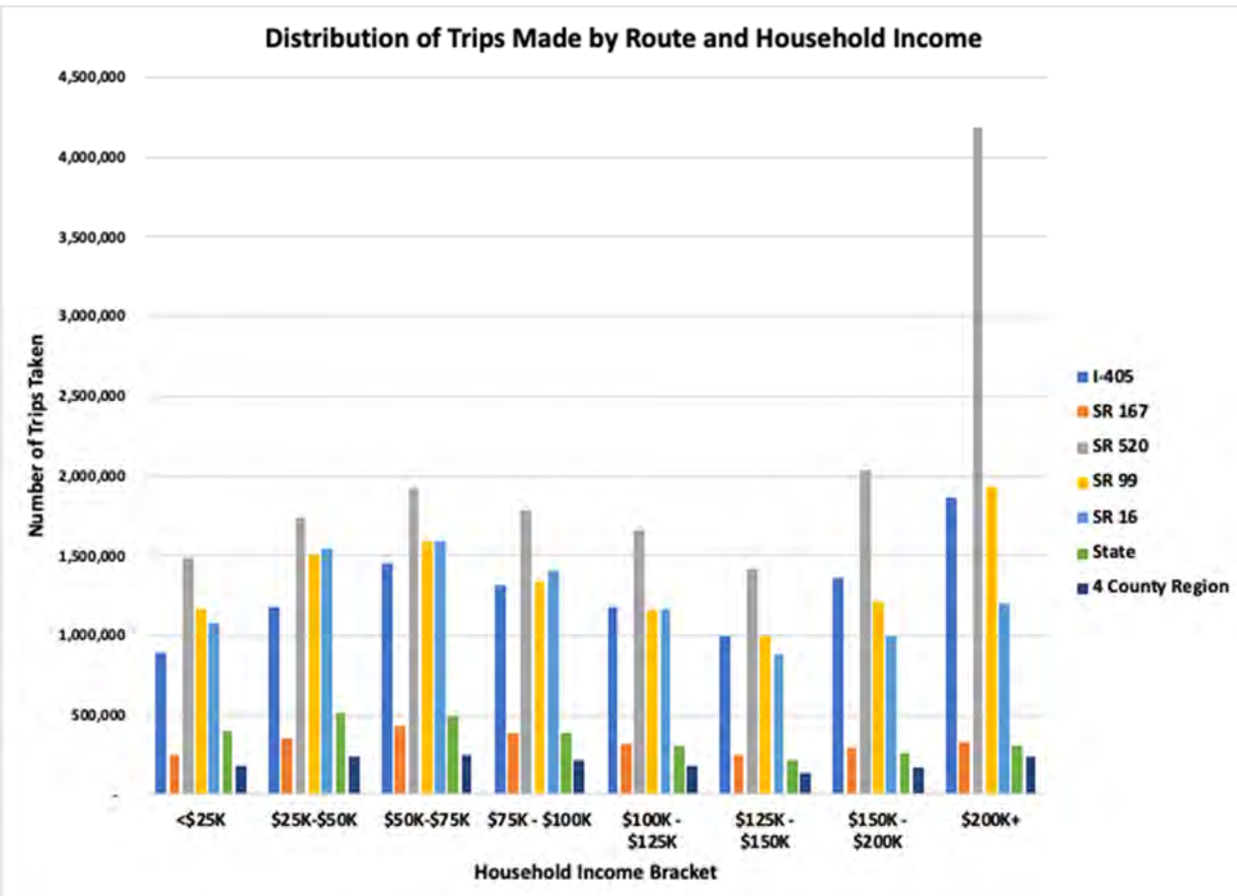

Figure ES-1: Number of Trips by Annual Household Income by Toll Facility

Among the key take-aways from Figure ES-1 are the much lower volumes of tolled trips on the SR 167 HOT (high-occupancy toll) lanes, partly because this is a one-lane facility in each direction and partly because there is less incentive to pay to use the facility during many hours of the day because the general purpose (GP) lanes next to the HOT lane are uncongested. A second major take-away is the very large number of trips taken on SR 520 by higher-income households. This is due to the combination of the SR 520 bridge being in a relatively wealthy portion of the region, the high capacity of the bridge (three lanes in each direction), and the very large demand for travel across Lake Washington.

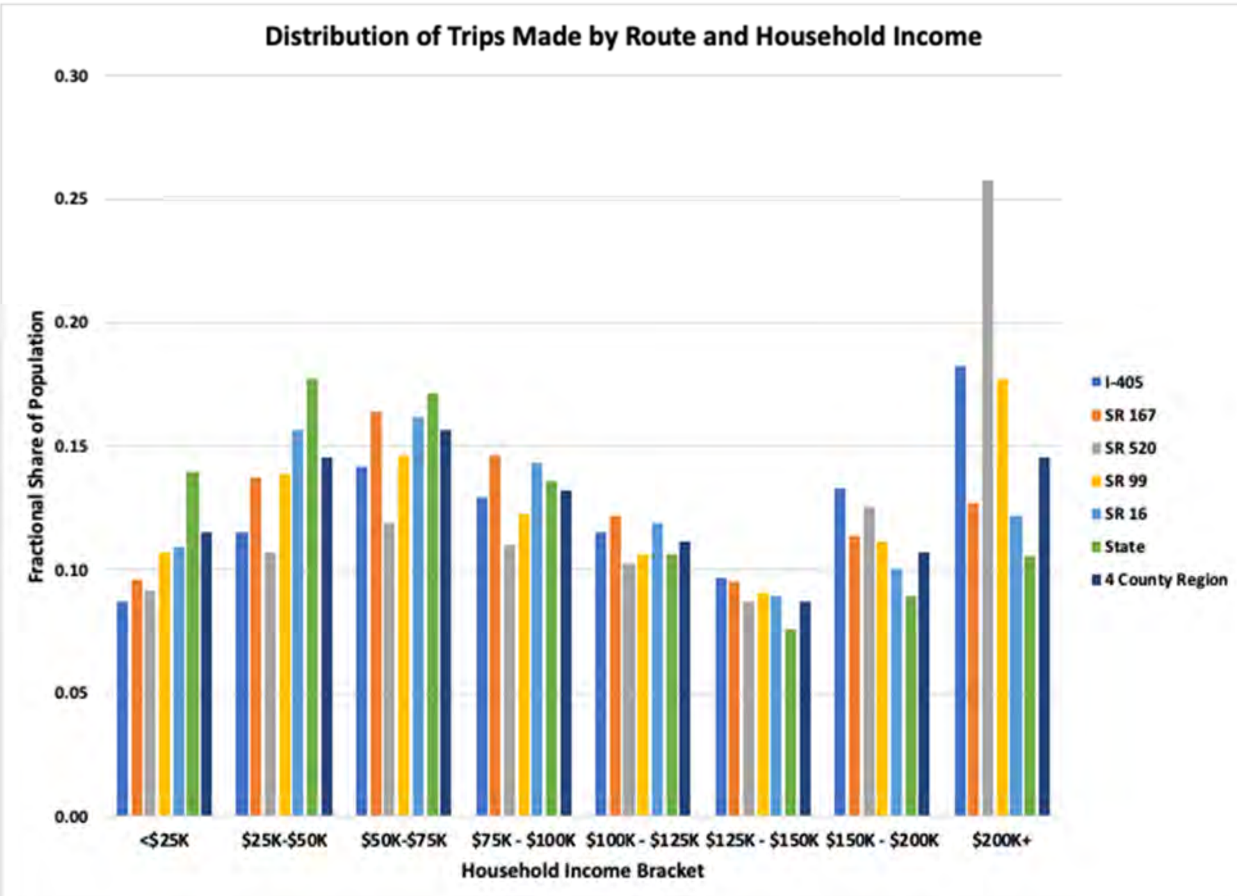

Figure ES-2: Normalized Distribution of Trips by Income by Toll Facility

In Figure ES-2, the effects of road size are removed by normalizing the Y-axis so that it shows the percentage of trip made, rather than the total number of trips. This figure provides a better understanding of the relative use of each of the toll facilities by households of different incomes, as now all trips are expressed as a fraction of trips made on that facility. Figure ES-2 also adds two new lines to the histogram, one for the distribution of household incomes for the entire state and one for the distribution of household incomes within the four-county Puget Sound region.

In Figure ES-2, the fact that the four-county region is wealthier than the rest of the state is apparent, given the relative size of the dark blue and green lines on the right side of the income distribution graph. This fact means that the costs of these expensive facilities are shifted away from many of the state's lower-income areas, outside of the Puget Sound region, and toward the higher-income populations that use them. It is also clear that a very large proportion of trips on SR 520 are made by the wealthiest households, while a disproportionate number of tolled trips on both the I-405 Express Toll Lanes (ETL) lanes and the SR 99 tunnel are also made by wealthier households. As a result, a larger share of the cost of these facilities is born by wealthier households. In return these households gain travel advantages. Also apparent in Figure ES-2 is that toll accounts from wealthier households are underrepresented on the SR 167 HOT lanes and the SR 16 Tacoma Narrows bridge, at least in relation to the overall four-county population. These facilities are interesting in that the middle-income categories ($60,000 to $125,000 annual household incomes) are slightly over-represented in toll payments on these roadways, whereas the wealthiest households are underrepresented relative to the region's population.

Figure ES-3 presents how frequently vehicles belonging to toll accounts[2] used the five facilities during the study year. This graphic shows that the majority of accounts using all five toll facilities use those facilities infrequently. Over 450,000 vehicles used the SR 99 tunnel once and only once between July 2021 and June 2022. This is 100,000 more single-use accounts than for any of the other four WSDOT toll facilities. In contrast, SR 520 had a greater number of accounts with vehicles that used that roadway frequently. This is true partly because of the high volume of use of SR 520 and partly because a large percentage of SR 520 accounts use the bridge routinely.

[2] "Accounts" include toll tag and pay-by-mail accounts with WSDOT, as well as the addresses of license plates whose owners have been billed because that vehicle was not registered with Good to Go!

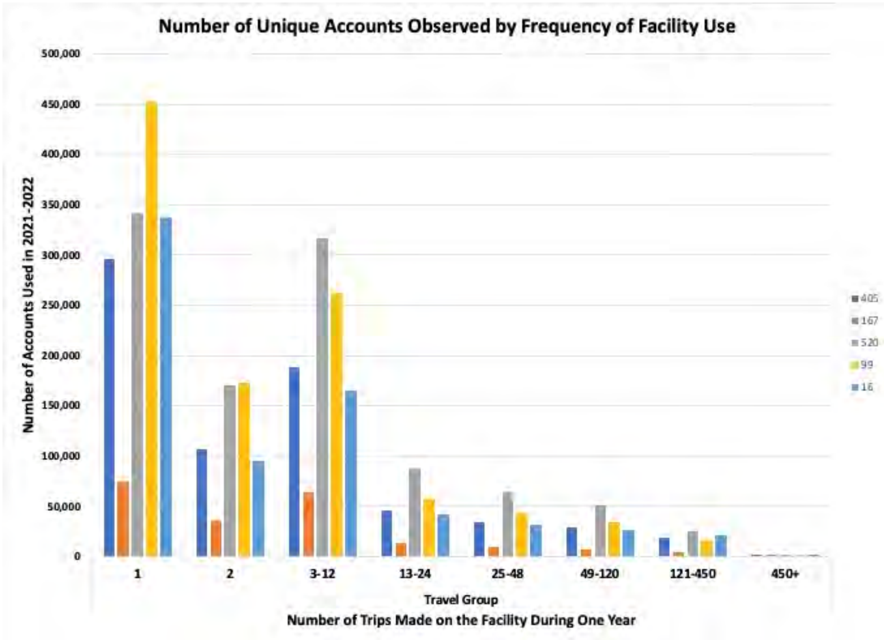

Figure ES-3: Number of Accounts Observed by Frequency of Facility Use

Figure ES-4 shows the same relationship between payment accounts that use a facility infrequently and those that use it frequently, but it normalizes that relationship to the total number of users on the facility. Figure ES-4 shows that despite the very large number of one-time users found on SR 99, SR 16 has an even higher fraction of one-time customers than SR 99. This is partly due to the fact that SR 16 carries a large amount of recreational travel—and thus individuals who use the bridge infrequently. It is also partly due to the fact that tolls are paid in only one direction on SR 16, so an out-and-back trip on SR 16 results in only one transaction whereas an out-and-back trip via the SR 99 tunnel results in two transactions.

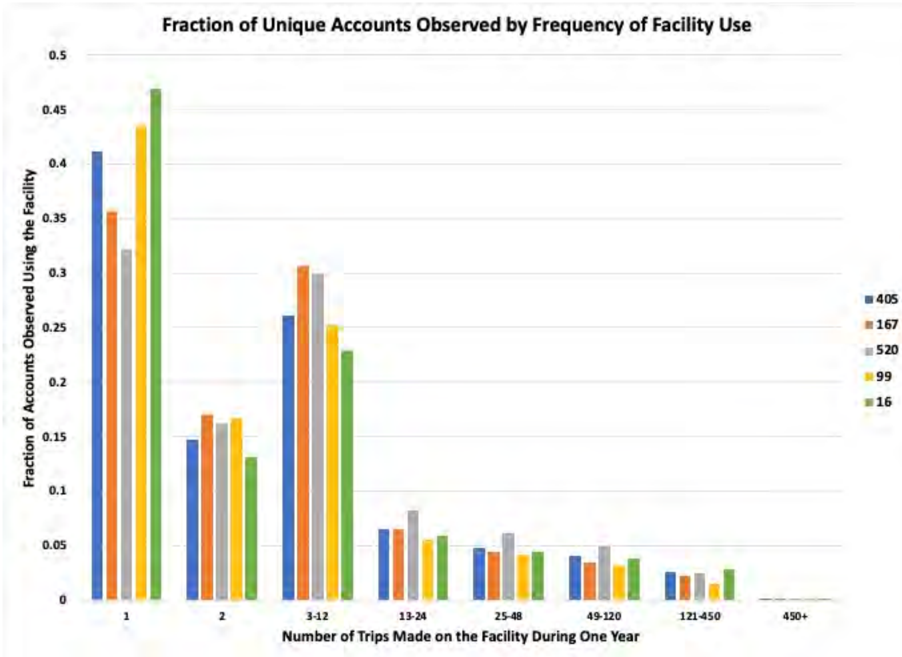

Figure ES-4: Fraction of Accounts by Frequency of Use by Toll Facility

Figure ES-4 also shows that SR 520 has a higher percentage of frequent bridge users. In addition, the graphic shows that SR 16 is somewhat unique in that it has a high proportion of one-time users and relatively high percentages of frequent users. Many of these frequent users are likely commuters who live on the Kitsap side of the bridge and work on the Tacoma side. Unlike SR 16, SR 520 has the lowest fraction of one-time users to accompany its above average number of high-frequency users. SR 99 is more oriented toward infrequent users, with among the smallest percentages of frequent users. Finally, SR 167 has more semi-frequent users than the other toll facilities.

The combination of figures ES-3 and ES-4 show that all five toll facilities are used by large numbers of users, with a large fraction of those users taking relatively few trips on the facility. The next topic examines the demographics of those users. User demographics are impacted by many factors, the travel opportunities each facility offers to each user, their ability to pay the toll price, and the relative travel benefits (e.g., travel time savings) the user obtains from using that toll facility, versus taking other alternatives. The relative benefits are a function of the alternative routes that users have when making trips served by the toll facilities.

For I-405 and SR 167, choosing to "not pay the toll" means simply choosing to use the parallel GP lanes and accept the difference in congestion between the GP and HOT lanes. No additional travel distance is required. For the more conventional toll facilities (SR 520, SR 99, and SR 16), not paying the toll requires the motorist to select an entirely different route. For SR 520, this typically means using I-90 or SR 522, although if coming from the north, it may mean driving north to I-5 instead of taking I-405 to SR 520. For SR 99, the most likely non-toll option is I-5, although City of Seattle surface streets are also an option. For SR 16, there are no realistic non-toll alternatives; the Washington State Ferries charge a toll, and while it is possible to drive west and south via SR 3 and then back north on I-5 through Olympia, this is not a realistic money saving alternative given the long distances involved.

Figure ES-5 shows the demographics of I-405 users. This graphic allows comparison of the ETL facility users as measured by the WSDOT toll payment system[3] and all users of the entire I-405 corridor (both GP and ETL lane users) as measured with location-based services[4] (LBS) data obtained through the Cambridge Systematics' Locus data system.[5] Figure ES-5 shows the relative proportion of all users of I-405 by income group. The blue color shows the fraction of users on the entire facility (GP and HOT lanes combined) in each income strata for the northern half of I-405. The grey color shows the income distribution of just the ETL users, while the yellow color shows the income distribution of the 4-county region.

The differences between the blue and grey lines in Figure ES-5 are primarily due to the difference between the use of the GP lanes and the Express Toll Lanes. It shows that for all annual household incomes below $100,000, a higher percentage of users are observed in the LBS data exceeds than are observed in the WSDOT payment data. This indicates that a smaller fraction of lower-income households use the Express Toll Lanes than use I-405 in general. This relationship flips when annual income climbs above $125,000. Higher income households make up a higher percentage of the ETL users than they do I-405 in general. Thus, higher-income households choose to pay to use the ETL more frequently than do lower-income households, given how often both groups use I-405 at all. Both the LBS and WSDOT payment data indicate that above $100,000 annual household income, higher-income households use I-405 at a greater rate than these

[3] The grey lines in the figure.
[4] LBS data are time and location datapoints collected by mobile phone applications. They are collected by private companies and can be converted into vehicle traces, which allow determination of the home location (census block group) of the phone (to which demographic information can be attached), the origins and destinations of trips made by the phone, and the routes taken by the phone. This allows estimation of the demographic profile of all users of I-405 for the roadway segments containing the I-405 Express Toll Lanes. Unfortunately, LBS data cannot effectively distinguish between HOT lane and GP lane users.
[5] The blue lines in the figure.

households are present in the region. This is in part due to the wealth of the communities through which I-405 crosses and in part due to these households traveling more often than lower-income households and also more often by car. Figure ES-5 also shows that higher-income households use the ETL facility at a greater rate than they use I-405 in general. This makes sense in that they are likely to have sufficient disposable income to be able to afford the improved travel time outcomes provided by the ETL more often than vehicles associated with lower-income households.

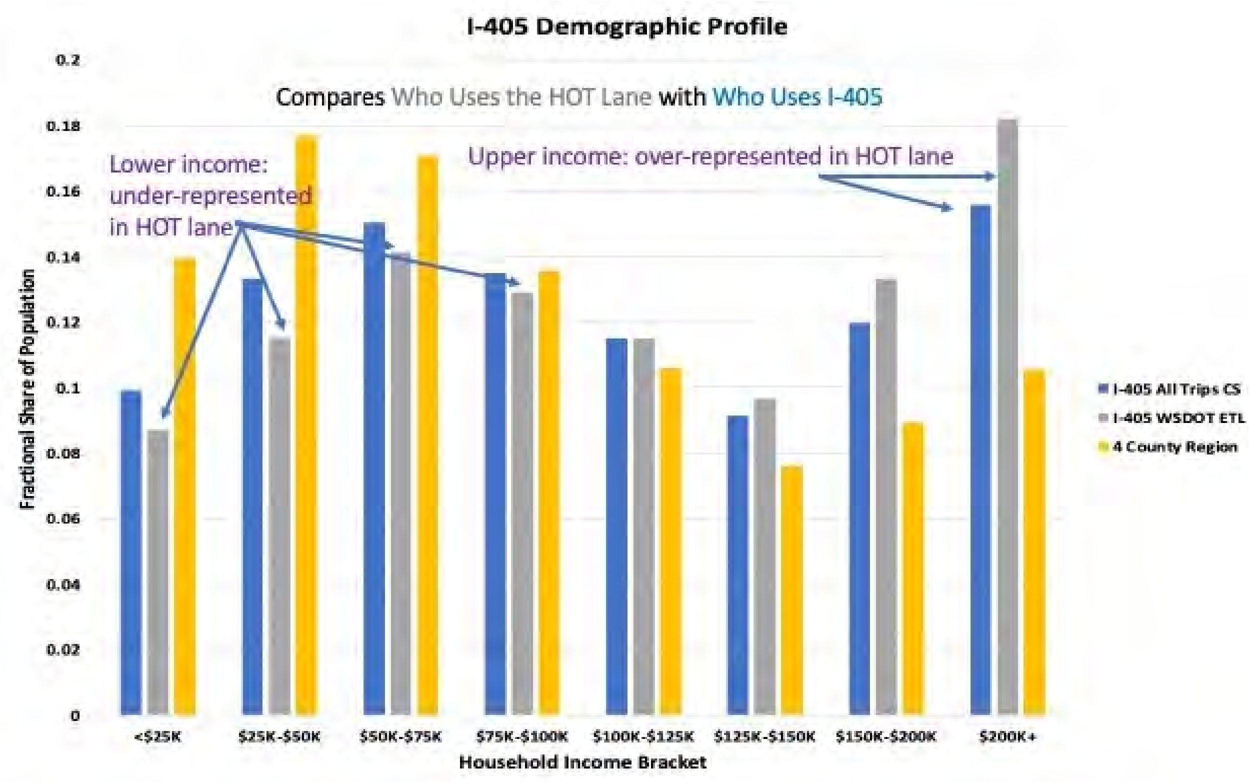

Figure ES-5: Demographic Profiles of I-405 Users

Conversely, as seen on the left side of Figure ES-5, lower-income households, which make up 14 percent of the regional population, are under-represented as users of I-405, both on the facility in general, where they make up 10 percent of the users, and in the Express Toll Lanes, where they are just less than 8 percent of the population. Unlike the higher-income households, when they do use I-405, lower-income households are more likely to be found in the GP lanes than in the Express Toll Lanes.

Figure ES-6 shows this same basic demographic information for SR 520, except that by using LBS data, it was possible to determine census block groups for trips with specific origin/destination (O/D) pairs for which the use of SR 520 makes sense. Given O/D pairs that generate trips that use SR 520, LBS data were used to identify trips between those same O/D pairs that do NOT use SR 520. Then the number of those trips using SR 520 and the number choosing alternative paths could be determined.[6] Consequently, Figure ES-6 shows not only the distribution of trips paying to use the facility as measured by WSDOT payment data, but also the fraction of trips by household income category that use the bridge as measured by the LBS data and the fraction of trips that make similar trips but choose to use different routes (e.g., I-90 or SR 522). In Figure ES-6 the difference between the blue and grey lines is caused exclusively by the differences in the LBS sample data and the WSDOT toll payment system, whereas in Figure ES-5 the difference in these lines is due partly to the sampling of trips by the LBS system and partly to the fact that the LBS data measure total use of I-405 north of downtown Bellevue, while the WSDOT data include only users of the HOT lane.

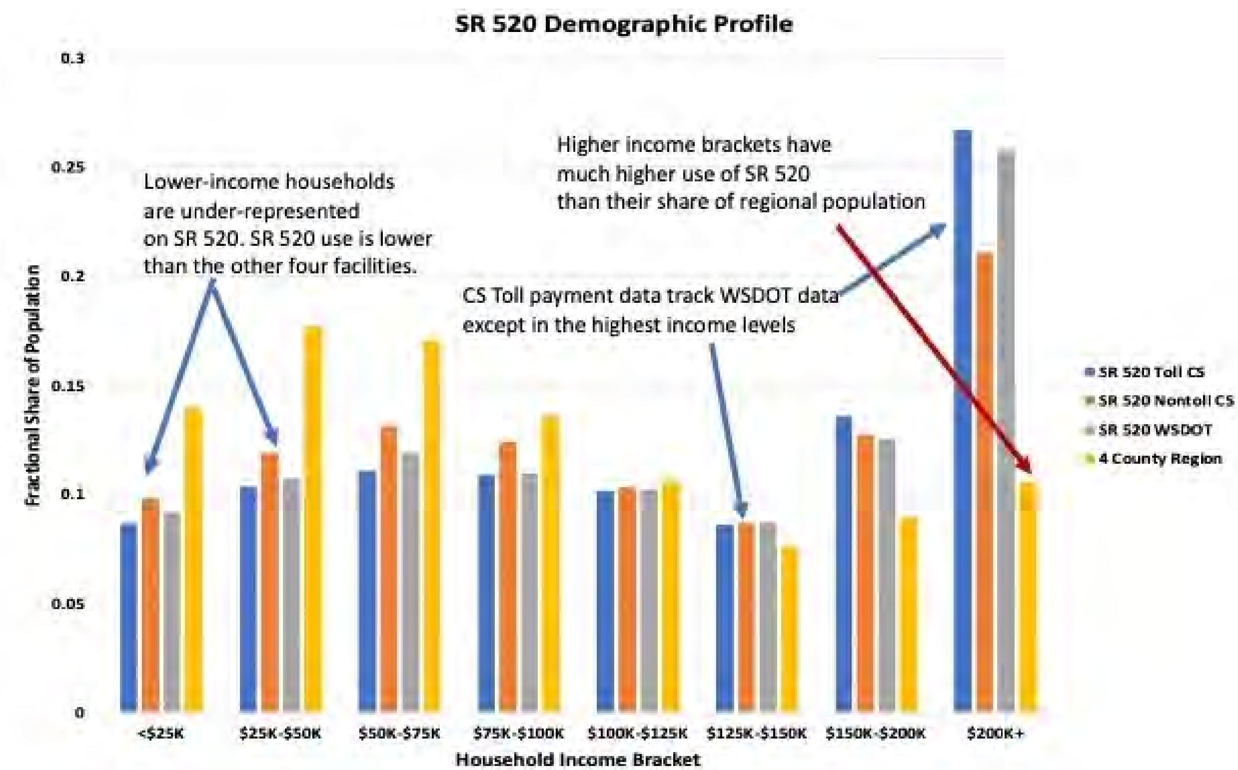

Figure ES-6: Demographic Profile of SR 520 Users

Figure ES-6 shows that those in the highest income household bracket make over 25 percent of the cross-lake trips on the bridge. This is observed in both the LBS and WSDOT data

[6] Because all passenger vehicles using SR 520 must pay a toll, it is not necessary to differentiate between those paying tolls and those that do not pay but still use the facility, as is required on I-405.

(blue and grey lines). At the same time, 20 percent of the cross-lake trips that avoid the toll by using I-90 and SR 522 (orange lines) are made by these same household income brackets. The higher the income bracket, the more likely that the trips occur on SR 520 and the less likely that they occur on alternative routes. Not surprisingly, higher levels of income result in a greater willingness to pay for faster travel times.

Drive-around trips slightly exceed paying trips for comparable origins and destinations for annual household incomes below $100,000. (Note that these summary statistics cover a wide range of origins and destinations, and the relationship between SR 520 and non-SR 520 trips varies considerably between O/D pairs.)

The last major point to extract from Figure ES-6 is that, with the exception of the highest income brackets, the fraction of SR 520 users—both toll paying and toll avoiding—is lower than that income bracket's share of the regional population. This reflects the fact that the SR 520 corridor is much wealthier than the region as a whole, and therefore the O/D pairs that supply most potential SR 520 bridge trips skew to the higher-income brackets.

Figure ES-7 shows the demographic profile of the SR 99 toll corridor. It is similar to that of the SR 520 corridor in that higher-income households make a disproportionate fraction of the trips through the SR 99 tunnel, although the fraction of trips made by these households is much lower than that observed on SR 520. The overall user profile is much closer to the regional profile than that observed on SR 520. This is in part because the geographic areas of the city that contribute a large share of SR 99 trips have lower incomes than those areas served by SR 520.

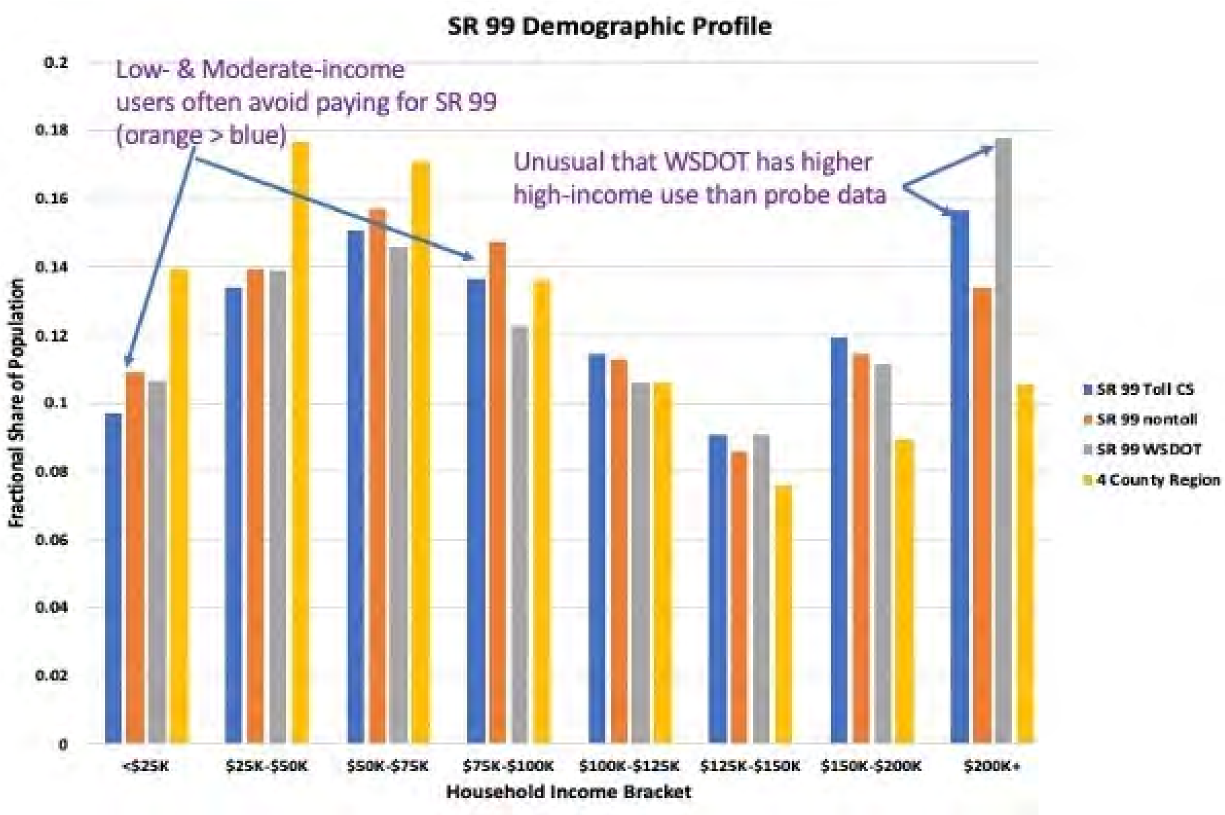

Figure ES-7: Demographic Profile of SR 99 Users

Also apparent in Figure ES-7 is that households below $100,000 annual income make a larger fraction of their potential in-corridor trips by selecting non-tolled alternatives, whether on I-5 or on surface streets along the Seattle waterfront. For example, households with incomes under $25,000 annually, represent 9.7 percent of the trips that use the SR 99 tunnel, but make just under 11 percent of trips from those origins/destinations that use the facility. In comparison, households making between $150,000 and $200,000 annually make up 12 percent of the toll paying users, but only 11.4 percent of the trips between similar origins and destinations. Households with annual incomes above $200,000 represent 15.6 percent of SR 99 tunnel users, but only 13.4 percent of users making comparable trips.

For SR 99, the number of non-tolled trips relative to tolled trips is also quite high. This can be seen in Figure ES-8, which illustrates the number of both tolled and non-tolled trips (for similar O/D pairs) observed in the LBS data for the SR 99 corridor.

Figure ES-9 shows the relationship between tolled and non-tolled trips, by annual household income level for trips made between origins and destinations where SR 99 is a common option. The fraction plotted shows the fraction of all trips observed in the Locus data made by households with the stated annual income level. For households with less $100,000 annual income or less, the fraction of trips made via non-tolled routes exceeds the fraction of (tolled) trips made using the SR 99 tunnel. Above $125,000 annual income, the fraction of trips made using the tunnel is higher than the fraction made using non-tolled routes. This shows that higher income households are more likely to pay the toll in order to gain travel time advantages, given the relative desire to make those trips, as their proportional trip making increases on the toll facility relative to overall regional trip making. That is, households with incomes above $200,000 make roughly 13 percent of trips travel shed served by the SR 99 tunnel, but they make almost 16 percent of trips in the tunnel. Meanwhile, households with incomes between $50,000 and $75,000 make just under 16 percent of trips in the travel shed, but only 15 percent of the toll trips in the tunnel.

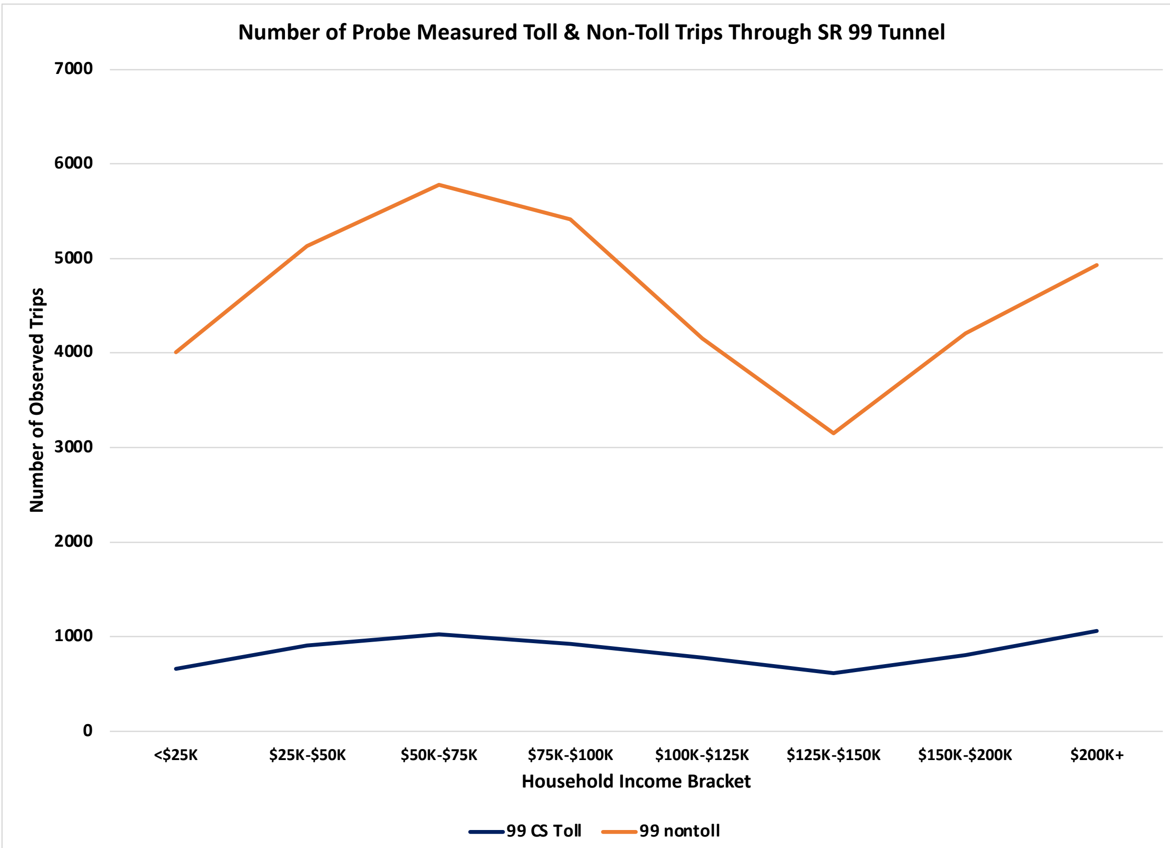

Figure ES-8: Volume of SR 99 Toll Trips vs Non-Toll Trips from LBS Data

Figure ES-8 shows that the overall SR 99 travel corridor is heavily used by moderate income households, and those travelers make considerably more non-tolled trips than tolled trips. The high ratio (typically greater than 4 to 1) of non-tolled to tolled trips is true for even the highest income brackets, which indicates that for many trips, SR 99 is likely the “alternative” route, used only when the preferred route (often I-5) is heavily congested, and SR 99 provides a superior option.

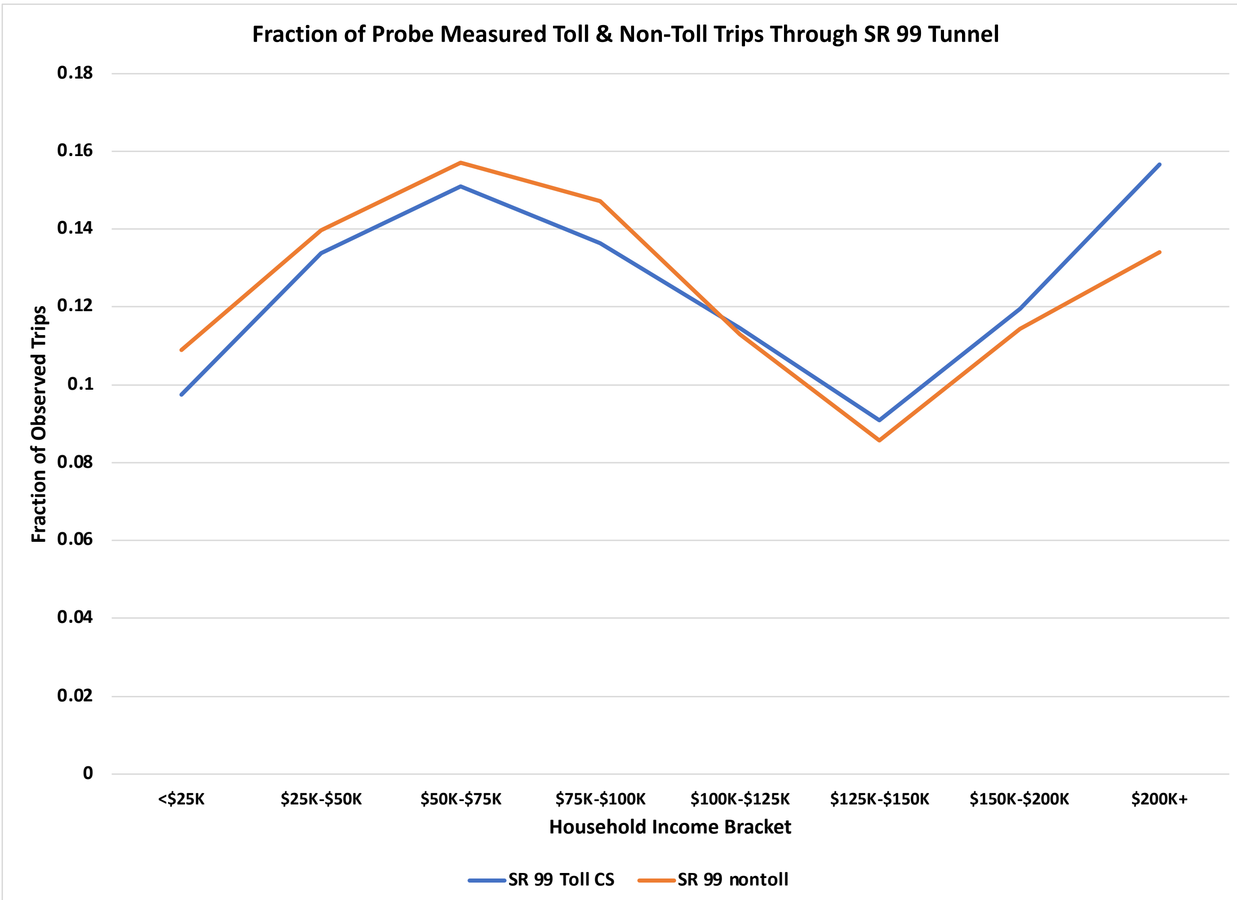

Figure ES-9: Fraction of Potential SR 99 Trips: Toll Vs Non-Toll

Figure ES-10 shows the final demographic profile, which illustrates the use of the SR 16 Tacoma Narrows Bridge. As seen with SR 99 above, the overall demographic user profile is similar to that observed in the overall regional population. However, unlike all previously presented toll facilities, the data from WSDOT's toll transaction system show that higher-income households are under-represented as users of SR 16 in comparison to their proportion of the regional population. Interestingly, the LBS data suggest that these higher-income households are present in excess of their share of the regional population. The project team believes that this is a function of the slight over-representation of higher-income households in the LBS data. (Higher-income households are more likely to own smartphones.)

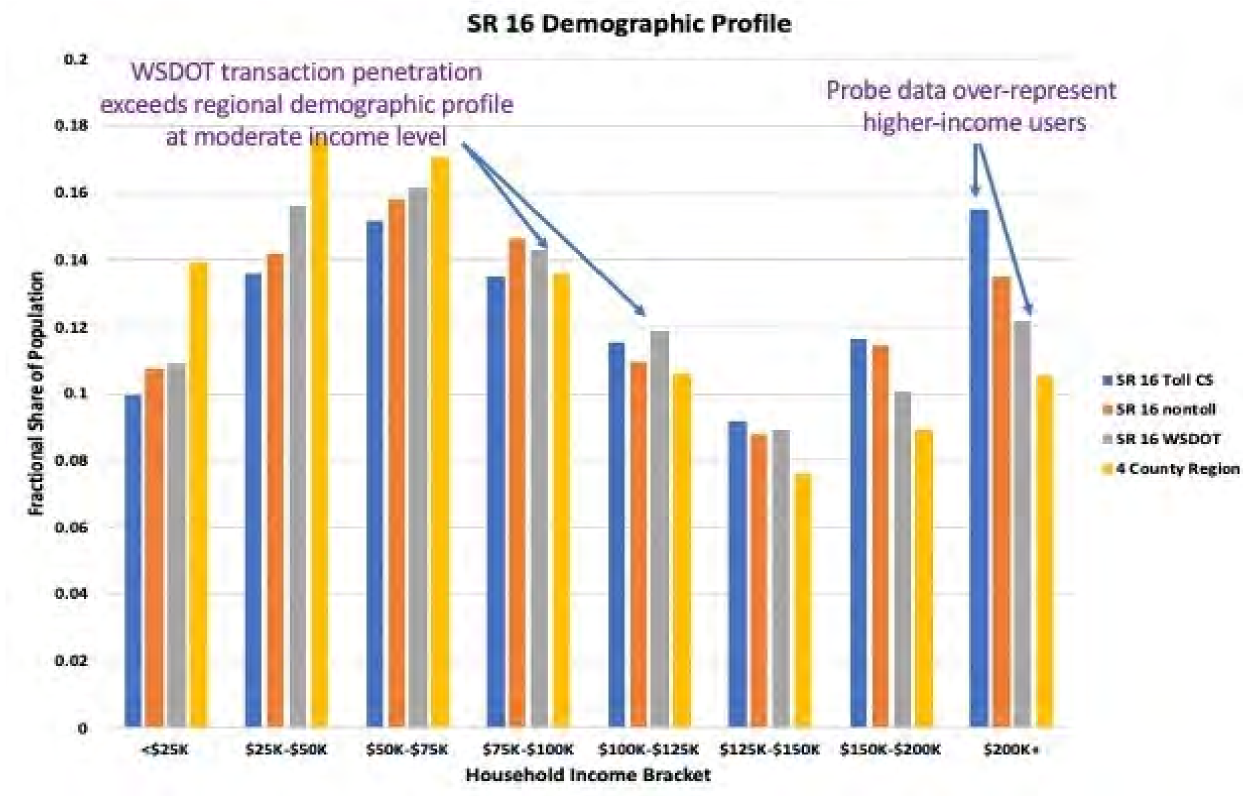

Figure ES-10: Demographic Profile of SR 16 Users

Figure ES-10 also shows that SR 16 has the highest fraction of toll paying customers in the middle-income range, with more than 14 percent of toll transactions associated with households with incomes of between $75,000 and $100,000 annually. SR 16 also has the highest fraction of toll payments in all income categories from $100,000 down in comparison to the other four toll facilities. This is due in part to the lack of an alternative non-toll option and in part to the presence of more low-income households on the Kitsap peninsula that need to travel to urban areas south of the bridge for activities and services not available north of the bridge.

Value of Time, Value of Reliability, and Elasticity of Travel

One objective of this project was to examine how changes in travel behavior and roadway performance affect the values of time and reliability as observed on the I-405 Express Lanes, as well as the observed price elasticity on that roadway. Table ES-1 shows a comparison of these values from 2018 with those from the period of July 1, 2021, to June 30, 2022. These comparisons cover all paid travel in the Express Toll Lanes. (The main body of this report contains a more detailed breakdowns of travel on the facility.) Table ES-1 shows that while the observed value of time has increased slightly since the pandemic, the value placed on better travel reliability has declined significantly. Similarly, travel has become more price sensitive, with a 10 percent increase in price resulting in a 7.1 percent decrease in travel demand versus a 6.4 percent decrease in 2018.

Table ES-1: Values of Time and Reliability 2018 versus 2021/2022

Parameter	Year	
	2018	7/2021 – 6/2022
Value of time	$53.1 / hr	$56.6 / hr
Value of Reliability	$26.4 / hr	$14.0 / hr
Price Elasticity	-0.64	-0.71

While it is difficult to directly explain these observed changes in attitudes, likely contributors are I-405 corridor performance and changes in travel behavior due to the increase in telework for many technology professionals who historically travel in this corridor during peak periods. Congestion on I-405 has declined since the pandemic shutdown, resulting in roadways that break down less frequently. This may help explain the reduction in the value of reliability. At the same time, many workers commute to the office less often. The decrease in their number of commute trips, plus their experiences of having more time at home, may increase their willingness to purchase a shorter commute on the days that they do travel. (That is, if workers commute only two days a week instead of five, they may be more willing to drive instead of riding transit, and having to pay only once or twice instead of three to five times may encourage commuters to pay more for time savings, explaining the slightly higher value of time.) Still, this reasoning is speculative, as this project scope did not include a survey of individual commuters in the corridor.

The study also examined the value of time and reliability on SR 167. Unfortunately, the results of that effort were of mixed reliability. It can be said with confidence that the levels of roadway congestion experienced by northbound AM commuters are very different than those of southbound PM commuters, and those differences appear to result in very different behavior patterns and different levels of HOT lane use for the two directions of travel. Examination of different movements on the facility (for example, northbound movements from Auburn to I-405 versus from Auburn to Kent) also showed very different economic behavior. The result is an inability of the project team to produce the value of time and reliability estimates for SR 167 in which we have confidence. The details of the SR 167 analysis are described in the main body of the report.

Conclusions

The project developed numerous findings from the analysis of large amounts of data. The most significant of these are as follows:

- Among Western Washington residents, higher-income households are more likely to pay tolls, make comparatively fewer toll avoiding trips than moderate- and lower-income households.
- Higher-income households typically are over-represented on the toll facilities, although they are slightly under-represented on SR 16.
- Moderate income households are particularly well represented on the southern toll facilities (SR 16, SR 167).
- Higher-income households are significantly over-represented on SR 520, in large part because of its location relative to high income neighborhoods.
- Not surprisingly, the use of toll facilities is greatly influenced by the demographics of the travel sheds they serve.
- The observed value of time for those individuals paying to use the I-405 Express Toll Lanes has increased modestly since 2018, while the value of reliability has decreased more substantially. This may be due to a decrease in the observed levels of congestion in both the I-405 GP and HOT lanes.

Recommendations for Next Steps

While the analyses conducted with anonymized toll transaction and LBS data were very useful in describing behavior in numeric terms, these types of analyses are not able to explain decision-making behavior. The UW team recommends that WSDOT conduct a survey of WSDOT toll account holders that asks to monitor their use of the facility and asks questions about their decision-making process regarding when to use or not use toll facilities. Such a project would require permission from participants to use their identified data, and it would likely require renumeration to those users, thereby limiting sample size. However, it would generate data on the specific decision-making process that are not available from anonymized data. It would also allow the collection of confirmed household income data, which would help confirm the results of the statistical approaches used in this and previous WSDOT studies.

For example, this future study could examine the degree to which (or even whether) moderate-income facility users are relatively insensitive to the lowest toll prices on the HOT lane.

Or if this insensitivity occurs only in higher-income households. In addition, it would be possible to understand why they choose to use the HOT lane when little travel time benefit would be gained.

It is recommended that such a study be constrained to one (SR 167) or at most two (SR 167 and SR 99) corridors, as both those corridors have more modest user income distributions than I-405 or SR 520 and more travel options than SR 16. They therefore present the opportunity to gain the most insight into travel behaviors that best reveal the effects of tolls on travel equity.

The second recommendation for future work is to design and conduct a study that is specifically directed at understanding the impacts of geography on toll facility use, avoidance, and equity. For example, it might use PSRC's regional models for peak and off-peak traffic conditions to determine origin/destination pairs likely to experience both toll and toll-avoidance behaviors. Then data could be collected on actual travel time conditions for those O/D pairs from navigation sites for large numbers of days, and actual travel patterns could be observed in location-based services data for those O/D pairs to determine the impacts that day-to-day changes in traffic congestion have on decision making. That is, it may be possible to answer questions such as, "To what degree does bad congestion on I-5 drive use of SR 99, and to what extent is that behavior geography driven and to what extent is it income driven?"

Chapter 1. Introduction

The Washington State Department of Transportation (WSDOT) uses tolling as a key mechanism for managing demand on I-405, SR 167, SR 99, and SR 520 and for funding megaprojects such as on SR 16, I-405, SR 167, and SR 509. Tolls impose an expense on roadway users, and while tolls are true “user fees,” imposition of these fees can create equity concerns.

This project provides insight into the equity of WSDOT’s toll facilities. The outcomes from this project will serve as the part of basis for evaluating use of the facilities and the implications of that use on the equity of toll facilities. The project was designed to (1) provide WSDOT with a better understanding of the current use of the department’s toll facilities; (2) examine how the combination of household income and tolling affect the use of state roadways; (3) provide an understanding of how costs associated with toll facilities are currently being distributed; and 4) provide a baseline of use against which changes in those attributes can be measured given changing economic conditions (e.g., COVID-related changes in overall traffic levels) or policy decisions (e.g., the introduction of a low-income toll program).

The project also produced a stand-alone literature review describing income-based toll programs in the United States (U.S.) that are intended to reduce the equity disparities imposed on low-income communities by toll facilities. The literature review also identifies best practices and lessons learned. The literature review is available through the Washington State Transportation Center (TRAC) report website and through the WSDOT library.[7]

The project analyses used data from all five WSDOT toll facilities for the period July 1, 2021, through June 30, 2022. The analytical results from this project were also compared against similar results for I-405 from 2018, when a study on toll equity was conducted by the University of Washington’s (UW) Data Science for Social good (DSSG) program.

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[7] The TRAC report website can be accessed here: http://depts.washington.edu/trac/reports/
WSDOT research reports can be obtained by visiting this URL: https://wsdot.wa.gov/about/library-research-reports/research-reports

INTRODUCTION TO THE WSDOT TOLL FACILITIES AND THE STATE

WSDOT currently operates five roadway toll facilities in the state.[8] These are the

- SR 16, Tacoma Narrows bridge
- SR 167 HOT lanes
- I-405 Express Toll Lanes
- SR 520 floating bridge
- SR 99 Alaska Way tunnel.

These five facilities use four different approaches to tolling. Figure 1 shows the locations of the five toll facilities.

Figure 1: Locations of Puget Sound Toll Facilities

SR 16 was the first toll facility to be built and operated in the state since tolls were removed from all state routes in 1985. Tolls on SR 16 follow the traditional toll pattern of a single price per vehicle (with that price based on the number of axles), regardless of the day of week or time of

[8] This excludes the state ferry system, although ferry routes are technically part of the state highway system.

day. Tolls are collected in only one direction (southbound toward Tacoma). Tolls are intended specifically to pay for the new Tacoma Narrows bridge span.

In contrast, SR 167 was initially tolled as a pilot project, designed to demonstrate the use of value pricing concepts for more effectively managing travel demand. Tolls are paid to use what had originally been a high occupancy vehicle (HOV) lane that was converted into a high occupancy toll (HOT) lane. Carpools are allowed to use the SR 167 HOT lane for free, while the price paid by single occupancy vehicles varies dynamically based on traffic conditions in both the HOT lane and the neighboring GP lanes. All vehicles may use the HOT lane facility for free between 7:00 PM and 5:00 AM. The price paid between 5:00 AM and 7:00 PM is based on the estimated price required to keep the facility operating above 45 mph. Signs ahead of toll gantries on the HOT lane display the current price for using that facility. The price changes depending on demand and roadway performance, but once a traveler has made a payment for a particular trip, that is the price to be paid, even if conditions change and the dynamic price changes.

I-405 follows a tolling concept similar to that of SR 167, as both use dynamically computed prices meant to inhibit the formation of congestion in the HOT lanes by increasing the price as necessary to limit demand. However, I-405 differs from SR 167 in several ways. First, the price of a trip on I-405 varies with distance. The tolled portion of I-405 is broken into three segments between Bellevue and Lynnwood, and the price for using the facility is a function of 1) the number of HOT segments used, 2) the particular HOT segments used, and 3) the relative levels of congestion and demand for both the GP and HOT lanes in all three segments. Typically, travel in the northern-most segment is the most expensive, as that segment is limited to one lane in each direction of the HOT lane facility, whereas the southern two-thirds of the facility have two lanes in each direction and therefore greater capacity for vehicles and a tendency for lower congestion. As with SR 167, the price travelers pay is the price displayed on dynamic road signs where they enter the toll facility, regardless of the length of the trip they make. However, unlike SR 167, where motorists can enter and exit the HOT lane at will, I-405 has a limited number of HOT land entry and exit points.

SR 520 uses a different approach to tolling than either of the two HOT lanes. When tolls were re-instituted on SR 520 in 2011, WSDOT decided to use a static, time-of-day toll regimen. That approach is meant to generate funds to help pay for the bridge and the associated roadway improvements on either side of it. It is also meant to help manage demand, both by moving discretionary trips from the peak period to the off-peak period when the roadway still has capacity and by funding transit service improvements that help shift demand to transit and away from single occupancy vehicle use. Toll prices change by time of day and day of week, with weekday, peak period prices being highest. Static, time-of-day pricing was adopted to provide motorists with better price certainty than on I-405 and SR 167 because those two roads have easy, "free" options in the adjacent GP lanes, whereas the SR 520 tolls can be avoided only by either driving around Lake Washington or using the I-90 floating bridge, located roughly two miles south of SR 520.

This same static, time-of-day pricing used on SR 520 was selected for WSDOT's newest toll facility, the SR 99 tunnel. This toll tunnel replaced the seismically unsafe Alaskan Way Viaduct. It serves north/south travel along the Puget Sound waterfront through downtown Seattle. As with SR 520, the tolls on SR 99 are designed both to help pay for the tunnel's construction and to provide a limited amount of demand management, with higher prices in the weekday peak periods and lower prices at other times.

A key difference between these facilities in terms of who chooses to use them and who does not, is in the availability of "free" (non-tolled) alternatives. Using these "free" alternatives comes with the "cost" of potentially added travel time and distance, depending on the travel conditions on those alternative roads needed to go from the traveler's origin to their destination. For I-405 and SR 167, "not paying a toll" means simply choosing to use the parallel GP lanes and accept the difference in congestion between the GP and HOT lanes. No additional travel distance is required. For the more conventional toll facilities (SR 520, SR 99, and SR 16), not paying the toll requires the motorist to select an entirely different route. For SR 520, this typically means using I-90 or SR 522, although if coming from the north, it may mean driving north to I-5 instead of taking I-405 to SR 520. For SR 99, the most likely non-toll option is I-5, although City of Seattle surface streets are also an option. For SR 16, there are no realistic non-toll alternatives; the Washington State Ferries charge a toll, and while it is possible to drive west and south via SR 3 and then back north on I-5 through Olympia, this is not a realistic money saving alternative given the long distances involved.

DATA USED IN THE STUDY

This project used a one-year period between July 1, 2021, and June 30, 2022, for all analyses. This year-long period was selected because it provided time for at least some of the travel impacts of the COVID pandemic shut-down to wane and more "normal" travel patterns to resume.

Five major datasets were used in the analyses. These were as follows:

- WSDOT electronic toll transaction data,
- WSDOT address data, at the census block group level, associated with those toll transactions,
- WSDOT roadway performance data,
- census data,
- location-based services data supplied by Cambridge Systematics through its Locus data product.

Each of these data sources is described in more detail below.

WSDOT Toll Transactions and Account Address Data

WSDOT primarily collects tolls by electronically identifying vehicles and then billing the owners of those vehicles. This takes place in three ways:

- Vehicles carry electronic Good-to-Go toll tags and are billed through the accounts associated with those tags.
- Vehicle owners register their car's license plate with WSDOT; their vehicle is identified by camera systems that identify and read license plates; and they are billed based on the registration information on file with WSDOT.
- Vehicles are identified by their license plates, and for plates not registered with WSDOT, the registered owners are identified through a license plate look-up conducted by the state's Department of Licensing (DOL); bills are then mailed to those registered owners.

For vehicles that use license plate identification but are registered with WSDOT, an additional fee of $0.25 is added to the toll fee to cover the additional cost of reading the plate. For toll transaction payments that require assistance from the DOL, $2.00 is added to each transaction.

The WSDOT billing process collects a variety of data, and those data were used in this project to identify the details of each transaction. For each toll road transaction, regardless of the method used to identify the vehicle and bill the user, the data included the following:

- facility used,
- hashed identifier of the account observed,
- price paid (including carpool designation if appropriate),
- time and date of the transaction,

- the entry and exit points of the toll corridor (the first and last toll gantries at which the vehicle was observed) if the toll transaction was for either I-405 or SR 167,
- an indication of whether a toll tag account was considered a "commercial" account (a "commercial account" is defined as having six or more vehicles assigned to that account, and those trips were removed from the value of time and value of reliability computations), and
- the census block group associated with the account's billing address (a null value if a simple automated look-up of the associated home address did not return a valid census block group).

The census block group was used instead of the actual billing address to preserve the anonymity of all toll transactions. WSDOT toll tag data do not describe the origins and destinations of trips. However, when combined with census data, they do describe where accounts "live," which was used to describe the demographics of drivers making trips on the toll facilities.

For SR 167 and I-405 the toll tag data describe the entry and exit points used for the HOT lane portion of their trips. This allowed computation of travel time savings for those HOT lane trips, as the researchers computed both HOT lane and GP lane travel times from the first to last gantry of the trip being made.

Carpools are not noted in the WSDOT electronic toll records for SR 167 but are recorded for I-405. This is because cars without electronic tags are assumed to be carpools on SR 167, unless WSP enforcement personnel observe them to be violators. On I-405, carpools must "declare" themselves with the carpool tag designed for that purpose. Therefore, on I-405 cars without toll tags are assumed to be paying customers, and the license plates of those vehicles are used to generate the toll transaction record. Carpool tags can also be used on SR 167 but are not required.

Census Data

Census data by block group were obtained from the 2020 American Community Survey (ACS) for the entire state of Washington. Trips made by vehicles based outside of the state of Washington were not incorporated into the demographic analyses for this project.

The census data describe the demographics of households in each block group. The census data were used in concert with the WSDOT toll account data, as well as with Location-Based Services data, as inputs to the ecological regression process (see the Methodology section). This allowed the researchers to estimate the demographic characteristics of travelers making the trips observed on toll facilities and, in the cases of SR 167 and I-405, on the combination of both the HOT lanes and the GP lanes that operate parallel to them.

Location-Based Services Data from Cambridge Systematics' Locus System

Location-Based Services (LBS) data are time and location data collected by cellphone applications. These applications record where and when a phone is located and transmit those data to private firms. Data can be collected at a variety of time intervals, often as a result of the activities the phone is performing. For example, many navigation applications collect very frequent data on phone location (as often as every few seconds) when they are actively used for real-time navigation purposes. That same application may collect data less often (e.g., one location point every 15 minutes) when it is "open, but not in use" (meaning the application is open but is not currently being used, either because some other application is in use or because the phone is not in active use) and may even collect data very infrequently (e.g., once an hour) when the application is closed but still resident on the cellphone.

The data collection firms package the location data collected by multiple applications and resell those data to other companies. The basic data sold describe the times and locations of individual cellphones, with the IDs associated with each phone hashed to limit the reidentification of the phone.

One set of companies uses those data to estimate a variety of transportation performance statistics and then sells those statistics. These statistics can include historical roadway speeds by road segment, mode split estimates, origins and destinations for trip making, and traffic volumes. Mode split and trip origin and destination are developed by following specific (hashed) device IDs over time. When a device begins moving, a "trip" has started. When the device then stays stationary for a given length of time, that trip has ended. The distance traveled and path taken between when a trip starts and when it ends are used to identify the mode of the trip. The path taken during a trip can then be used to determine whether that trip used a specific roadway or roadway segment.

For this study, the project team used the LBS obtained and processed by Cambridge Systematics (CS) through its Locus data product. The Locus data used were for vehicle trips only. The data were processed by Cambridge Systematics to identify all vehicle trips, from origin to destination, along with the data points obtained between the beginnings and endings of those trips.

When it could be determined that the device (phone) being tracked had used one of the five WSDOT toll facilities, the data were extracted from the database and saved. The data saved included the following:

- hashed) device ID,
- WSDOT roadway used (this could be multiple toll facilities for one trip)
- the trip origin (the census block group in which the trip started),
- the trip destination (block group),
- the date and time the trip started,
- the date and time the trip ended.

CS summarized all of the O/D pairs that were used for trips across toll facilities and then extracted all of the trips between those O/D pairs. These trips were the “avoided tolls” trips. The same data were saved for these trips as for the “used the toll facility” trips.

Finally, CS examined the trip making behavior of all trips taken by each hashed device ID. On the basis of where that device started the most days, it was possible to estimate where that device “resided.” This location was identified only at the census block group level. This census block group was then assigned to each hashed ID to be used for identifying the household income associated with that device. Household income was identified by using the same ecological regression technique that was used to estimate household income for the WSDOT toll tags. (See the Methodology section for the description of Ecological Regression.)

The end result was the development of a dataset that described, at the census block group level, a series of trip tables with the origins to destinations of trips that used the WSDOT toll facilities and a comparison dataset for similar trips between those same origins and destinations that did not use the toll facilities. The travel times and travel time distributions for those trips could then be compared, along with the demographic characteristics estimated for each of the devices making those trips.

WSDOT Roadway Performance Data

The final dataset contained all of the roadway performance data collected by WSDOT through its freeway management system. These data are accessible to the public through the TRACFLOW system maintained and managed by WSDOT. The web interface for those data can be found at this URL: https://tracflow.wsdot.wa.gov/

The data obtained from this site and used in this project included the following:

- travel times for each origin/destination pair on both SR 167 and I-405 for GP and HOT lanes,
- traffic volumes and facility speeds at the mileposts closest to the entrance points to HOT lanes on both SR 167 and I-405,
- roadway performance contours (speed by time and location and frequency of congestion by time and location) for entire corridors, GP and HOT lanes in both directions.

Data errors (mostly locations on SR 167 where the loop detection system was unable to report valid data because of equipment error of one type or another) required the start and end points of some travel times to be moved slightly from their desired locations. The same was true for the travel time locations.

Table 1 shows the entrance and exit points used for both travel time computations northbound for SR 167. Table 2 provides the entrance and exit points for southbound SR 167. Table 3 gives the HOT lane entrance and exit points for the I-405 Express Toll Lanes northbound, and Table 4 provides the entrance and exit points for the southbound direction. In all four tables, an "X" indicates which pairs of entrances and exits were used to define trips on the HOT lane and were thus used to generate both HOT lane and GP lane travel times. The entrance points were also used to estimate the volumes and speed conditions at the point where drivers made the decision to enter the HOT facility. Note that this assumption was directly valid for I-405, as these are the points where drivers must make these decisions. For SR 167, they were the best available estimates of conditions at the point of decision because they were the first point at which the vehicle was observed using the HOT lane. However, because vehicles have free entry to and from the HOT lanes on SR 167, the actual points of entry might differ slightly from these locations.

Table 1: Northbound SR 167 Entrance and Exit Mileposts

Northbound Mileposts		Exit					
		14.76	16.87	19.01	20.68	23.42	25.07
Entry	13.75	X	X	X	X	X	X
	15.65		X	X	X	X	X
	16.28			X	X	X	X
	19.74				X	X	X
	21.39					X	X
	23.42						X

Table 2: Southbound SR 167 Entrance and Exit Mileposts

Southbound Mileposts		Exit							
		25.07	23.9	21.29	19.48	17.38	16.28	12.87	12.15
Entry	25.62	X	X	X	X	X	X	X	X
	24.45		X	X	X	X	X	X	X
	22.26			X	X	X	X	X	X
	21.29				X	X	X	X	X
	19.01					X	X	X	X
	17.38						X	X	X
	16.28							X	X
	12.87								X

Table 3: Northbound HOT Lane Entrance and Exit Points for I-405

Northbound Milepost		Exit							
		15.63	19.21	21.83	20.47	25.17	27.96	28.53	28.98
Entrance	13.60	X	X	X	X	X	X	X	X
	13.92	X	X	X	X	X	X	X	X
	15.63		X	X	X	X	X	X	X
	19.21			X	X	X	X	X	X
	20.22					X	X	X	X
	20.93					X	X	X	X
	21.83					X	X	X	X
	25.68						X	X	X
	27.96							X	X
	28.53								X

Table 4: Southbound HOT Lane Entrance and Exit Points for I-405

Southbound Milepost		Exit									
		27.44	26.16	25.17	21.83	18.70	20.93	16.12	15.08	13.60	13.92
Entrance	28.98	X	X	X	X	X	X	X	X	X	X
	27.44		X	X	X	X	X	X	X	X	X
	26.16			X	X	X	X	X	X	X	X
	22.31				X	X	X	X	X	X	X
	21.36					X	X	X	X	X	X
	20.93							X	X	X	X
	20.47							X	X	X	X
	18.70							X	X	X	X
	16.12								X	X	X
	15.63								X	X	X

Chapter 2. Demographics of Toll Users

This chapter describes who uses each of the toll facilities, and it examines their demographics and geographic distributions. Demographics were estimated by using two different datasets, WSDOT toll transaction data and location-based services (LBS) data provided by the Cambridge Systematics (CS) Locus data product. Both datasets track specific devices (toll tags, license plates, or cellphones) and can determine whether they are on a specific roadway based on either GPS traces (LBS data) or observation by toll revenue collection hardware.

The WSDOT data allow the identification of a "home" location for each device based on its billing address. These were provided by WSDOT to this project's research team at the census block group level for that address location to preserve the privacy of drivers.

The LBS trace data were used to identify the "home location" of each device. This location was defined as the census block group within which most overnight stays of the device occurred.

By assigning these census block group locations as the "residences" of the devices, the income distributions associated with these datasets were estimated by using a process called ecological inference. That is a technique commonly used in voting analysis research to discern disaggregate behavior from more aggregate voting behavior. (That is, to understand the voting patterns of individuals with specific characteristics given the aggregate voting totals being reported.)

The specific version of ecological inference used for this study was ecological regression. This technique is introduced in the next subsection of this chapter.

On the basis of those results, it was possible to estimate the income distribution associated with specific roads in the state, in particular WSDOT's toll facilities. These results are discussed in the following sections of this chapter.

METHODOLOGY

Introduction to Ecological Regression

An ecological regression model allows the relationship between individual-level quantities to be found from aggregate (or ecological) data (Jackson 2006). The key difficulty that ecological regression addresses is that group-level exposure may not be the same as individual exposure within an aggregate region, causing ecological bias (for more discussion see Richardson et al. 1987, Greenland and Morgenstern 1989, Greenland and Robins 1994, and Richardson and Monfort 2000). Ecological regression considers the within-area distribution of exposure to give a more accurate estimate of true individual exposure levels than other regression methods. Take for example an outcome count y_i in area i with population N_i. Typically, the model of y_i, using as an example a Poisson or binomial regression, utilizes the area-level covariates z_i. This, when binary covariates are used, shows the proportion of the population exposed in the area based upon each covariate. The typical regression models measure only the relationship between the aggregate exposures and outcomes. Therefore, these types of models are accurate only when each individual in area i has the same covariates z_i, resulting in a perfectly linear model. However, this is often not the case, as many real-world scenarios involve individuals in aggregate areas who have different covariates for certain key explanatory indicator variables. This deviation from the perfectly linear scenario is the direct cause of the ecological bias experienced by binomial and Poisson regression models (Richardson et al.1987).

To address these biases, ecological regression takes advantage of supplementary data sources, specifically individual-level data, to address the individual variation within the aggregate area. The model used is Goodman's Method of Bounds regression (Goodman 1959). This can be modeled with Equation (1):

$$logit(p_{ij}) = \mu_i + \sum_r \alpha_r x_{ir} + \sum_r \beta_r z_{ijr} + \gamma_{s_{ij}} \tag{1}$$

where: p_{ij} is the total risk for an individual outcome y_{ij}

j is each individual

i is each area

x_{ir} is each group level covariate

z_{ijr} is each individual level covariate

α_r is each grop level coefficient

β_r is each individual level coefficient

μ_i is the baseline risk

$\gamma_{s_{ij}}$ is the multistrata risk across each strata s

From this equation, the average risk for an individual in area i can be found by integrating the individual model over the joint within-area distribution of covariates. This is shown in Equation (2):

$$p_i = \int p_{ij}(x) f_i(x) dx = E_x\left(p_{ij} \middle| i\right) \qquad (2)$$

where: p_i is the average risk for an individual in area i

The quality of this information is enhanced when it is corroborated with individual-level data within each region. These individual data, which contain data on a subset of individuals in each region, allow for the model to ensure accuracy of the individual covariates (Richardson et al. 1987, Wakefield and Salway 2002, Prentice and Sheppard 1995). This allows the average risk for each individual to be better calibrated to actual outcomes.

The output of an ecological regression model is inherently probabilistic: generally speaking, it indicates the likelihood that an individual in an aggregate dataset fulfills a given category of interest (Jackson 2006). A key implication of this is that this method is only statistically valid when the results of the model are re-aggregated together. This means that the model is not accurate at inferring characteristics about specific individuals in a dataset but is accurate only over a relatively large sample.

This method originated in the fields of medicine and political science, where this ability to infer individual characteristics from aggregate data has been paramount (Gelman et al. 2016). In the medical field, this has been necessary because of the nature of clinical trials, which require the anonymization and therefore aggregation of clinical data even though the prevalence of a disease is an inherently individual trait. Similarly, in the field of political science, this has been used to understand the voting habits of individuals from differing demographic groups based upon aggregate, anonymous survey data.

Ecological regression is seldom used in the context of transportation, although there are some examples. In one such example related to traffic safety, a Bayesian ecological regression models were created to analyze road mortality in both Europe and Tunisia (Eksler et al. 2008) (Kammoun 2020). Both studies utilized ecological regression to isolate the individual-level characteristics that led to traffic collisions as a way to determine risks associated with each geographic region. Both studies found that, generally speaking, collision rates decreased as the population density increased, indicating that rural areas carried higher collision and fatality risk than urban areas. It is important to note that these studies utilized Bayesian ecological regression, which is a different method of ecological regression than the Goodman's Method of Bounds regression used here.

Ecological regression has already been used in some cases to understand equity issues, such as the representation and distribution of benefits to toll facility users (Leung et al. 2019). Ecological regression allowed that study to connect the benefits gained by using the toll facility to the demographics of those using the toll facility. It found that while the net benefits of using the toll facility were much higher for high-income individuals, low-income individuals experienced a greater net gain per trip, indicating that this toll facility was generally equitable. In another example in Baton Rouge, Louisiana, ecological regression was used to study the socio-demographic and spatial effects on ridership of the transit system (Kuai 2020). Semi-parametric, geographically weighted regression was used, and the researchers found that neighborhoods with higher concentrations of non-white minorities, recent immigrants, and carless households most positively influenced public transit ridership. This is one example of many potential equity analysis scenarios that could benefit from a more direct understanding of the critical demographics being studied.

Methodology for the Tolling Equity Study

In this study, we utilized ecological regression to determine the demographic profiles of the users of each facility. This was an optimal regression technique to use because of its ability to infer characteristics at an individual level; the choice to use a toll facility occurs on an individual level and is determined by the individual characteristics of each user. Although many characteristics can influence an individual's choice to use a toll facility, the characteristic that this regression model assessed was household income. All of the toll transaction data we gathered from the use of the facilities provided information on only the geographic location of the residence that paid a toll; we had no direct information connecting any toll payment account with a particular income level. We drew our household income data from the American Community Survey (2021 data release) of the U.S. Census. Critically, these data are aggregated geographically into census block groups (CBGs) as opposed to being aggregated by income level. This was convenient because it could directly connect with the geographic home locations of the toll users; however, there was no direct connection between each particular user and their income level, and we knew that income does influence an individual's choice to use a toll facility beyond simple geographic delimitations (Leung et al. 2019). Therefore, ecological regression allowed us to extract the individual-level characteristic of income to probabilistically assign the income level of each toll trip based upon the characteristics of the home CBG of the account associated with that trip.

To extract the statistical demographic models for each facility, we had to create a separate model for each facility utilizing only trips for that facility because travel behavior may not be similar among all facilities. To build each model, we first assigned each account that used the tolling facility to the income demographic profile of its home CBG. This income profile then became the explanatory variable for our model, such that it could predict how over- and under-represented each income strata was for the facility. This over- and underrepresentation could then be applied back to each trip taken on that facility as a probability that a trip was made by each income strata. When aggregated together, this provided a statistically accurate representation of the population that used the tolling facilities. It is important to note that these probabilities had little meaning on a trip level, i.e., it would be inaccurate to say that a particular trip from a particular account, and therefore the household income of that account, was likely of a particular stratum. Instead, this provided insight into the overall profile for the facility. Once the number of trips for each income strata had been calculated, the percentage of trips taken by each stratum on each facility could be calculated such that the relative use of each facility by vehicles of each strata could be directly compared. This also allowed us to compare the findings to overall demographic profiles of the region to understand differences between the total populace and those who used the toll facilities.

Data Preparation

To prepare the WSDOT toll transaction data and the CS LBS data for use in the ecological regression process, the following additional data preparation steps were required.

WSDOT Data

WSDOT toll transactions contain all vehicle observations. For the equity study, we desired to remove commercial accounts from the database, as those vehicles are not appropriately included in equity analyses. Working with WSDOT, we decided that determining which toll transactions to assign to “commercial accounts” would be based on the number of tags or license plates associated with a single account billing address. When six or more tags or license plates were associated with a single account, that account was considered a commercial account.

Transactions associated with vehicles designated as “commercial” were then removed from the analysis.

This assumption did fail to identify a small number of smaller commercial enterprises. These vehicles may in fact have been the reason that very low-income households were identified as using the toll systems. The ecological regression process assigned a small fraction of vehicles to low-income households in those census block groups in which those individuals lived. In some cases, it is likely that vehicles associated with small companies were parked in those census block groups. Because they made trips on the toll facilities (paid by the companies), these trips were assigned to that census block group and thus assigned to the lower-income households that lived in those block groups. Unfortunately, it was not possible within the scope of this project to define the size of these errors, but they were likely small, given the relatively small number of trips involved.

Location-Based Services Data

The primary data reparation task required for the LBS data was the determination of whether a trip used a WSDOT toll facility. To make this determination from the trace data (consecutive time and location data points for specific devices), a map matching and road assignment process taken from an article titled “Map-matching for low-sampling-rate GPS trajectories." (Lou et al. 2009). Extending that work, the CS technique also used a dynamic routing function to interpolate routes between trace location points when those points were very sparse. When the trace—as interpolated—used one of the WSDOT toll facilities, that trace was identified with that facility.

FINDINGS

Introduction and General Visualizations

Once the toll transactions and LBS data had been assigned to specific income distributions by the ecological regression model, it was possible to graphically represent the use of the five toll facilities based upon income. Two separate techniques were used to aggregate census block groups into visual categories to help explain behavior. Separate graphics were devised for each aggregation technique. In both cases, ten groups of census block groups were identified. For all visuals, regardless of the grouping technique used, the darker the geographic representation of the census block group, the higher the concentration of the variable being examined (typically the number of trips or the number of accounts associated with that block group), and lighter areas showed lower amounts of that variable.

First, a statistical technique called the "Jenks Natural Breaks" methodology (ESRI 2022) was used to identify block groups with similar behavior. This technique looks to define groups with a low level of variation within a group and a large distance between it and the next group. The downside of this technique is that the groups vary from analysis to analysis, making it difficult to compare analysis results. That is, the maximum number of trips allowed to be in the "least trip making" set of zones for one set of analyses may be very different than the maximum number allowed for the next analysis. That makes it difficult to compare answers to questions such as, "Where are the smallest trip making zones?" from one analysis to another, as the number of trips in the "smallest" category can be very different among analyses.

As a result, a second set of analyses was run, in which the cluster groupings were held constant across comparable analyses. This allowed direct comparisons of the locations of zones within each group size.

Statewide and Puget Sound Region Income Distributions

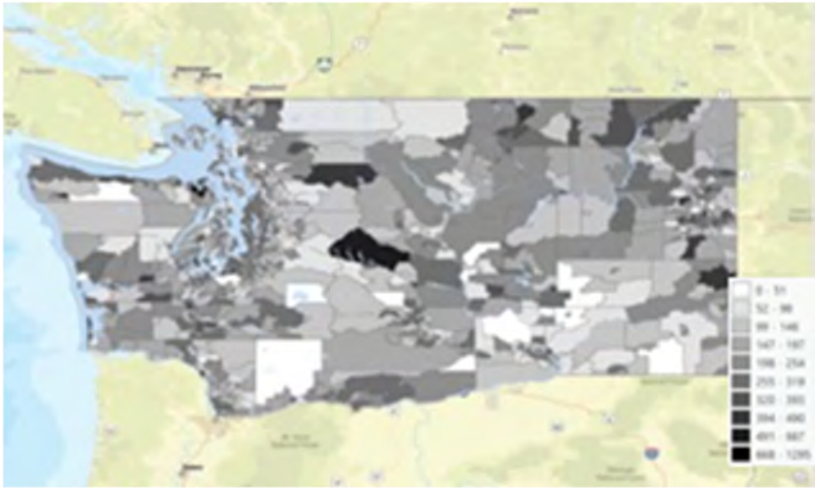
To set the stage for the analysis of income distributions for motorists using the five toll facilities, it is important to first discuss the distribution of incomes across the State of Washington.

We decided to not use a single aggregate metric to visualize income, such as a mean or median income of a geographic region, because the project was interested in describing both the shape and value of the income demographic profile, not just a single value. For example, take two census block groups (CBGs) A and B, where A has ten households that each have an annual household income of $100,000, and where B has five households with an annual household income of $25,000 and five households with $175,000 annual income. An aggregate measure such as the mean for the ten households would indicate that these two CBGs are the same, since both have a mean household income of $100,000. However, we can see that the actual household income composition of these CBGs is very different. This is a simplified example, but it illustrates the issue of using a single aggregate measure to define income. Therefore, the figures that follow show present yearly household income distributions in state CBGs in four quadrants. These are defined as the number of households in that CBD with up to $49,999, from $50,000 to $99,999, from $100,000 to $149,999, and $150,000 and above annual household income. Although this is still not a perfect visualization of the true distribution of incomes, it gives a better idea of the shape of these distributions than a single aggregate measure.

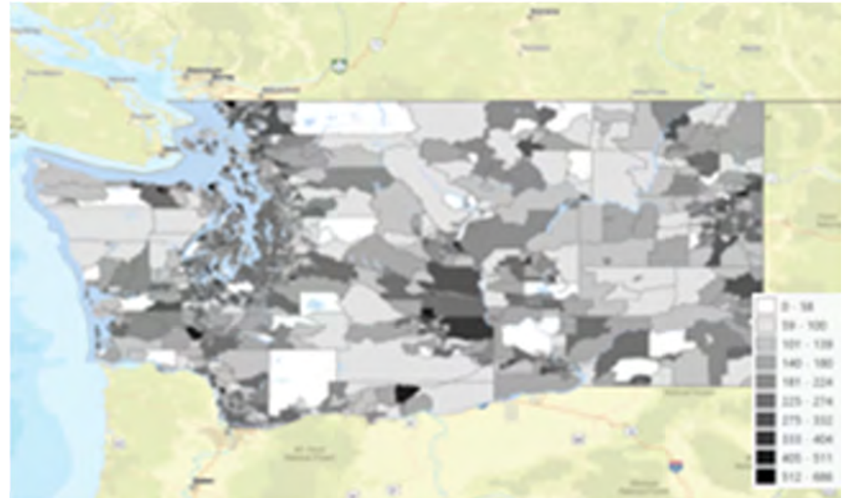
In the first set of four graphs (Figure 2), the Jenks Natural Breaks technique was used to group CBGs by the number of households within each CBG. This means that the absolute values associated with the four different images in each figure differ. The legends for each image must, therefore, be used to compare the relative magnitude of the number of households described by each color gradation. Figure 2 shows the income level within the four quadrants for the entirety of Washington state across four separate images. Figure 3 shows income levels for just the Central Puget Sound region, the main population center for the state and the location of all of the toll facilities. In both sets of maps, the darker the coloring, the more households that are present within that income category.

From these figures, general trends in the income distribution for the state can be observed. First, CBGs east of the Cascade Mountains tend to have more low-income households and fewer high-income households than CBGs west of the mountains. This makes sense, as east of the Cascades tends to be more rural whereas the west tends to be more urban, which correlate to lower and higher incomes, respectively. In looking more closely at the Central Puget Sound region, the closer to downtown Seattle, downtown Bellevue, or the eastside of Lake Washington, the greater the number of higher-income households. There is an especially large concentration of the highest quadrant of income on the eastern side of Lake Washington.

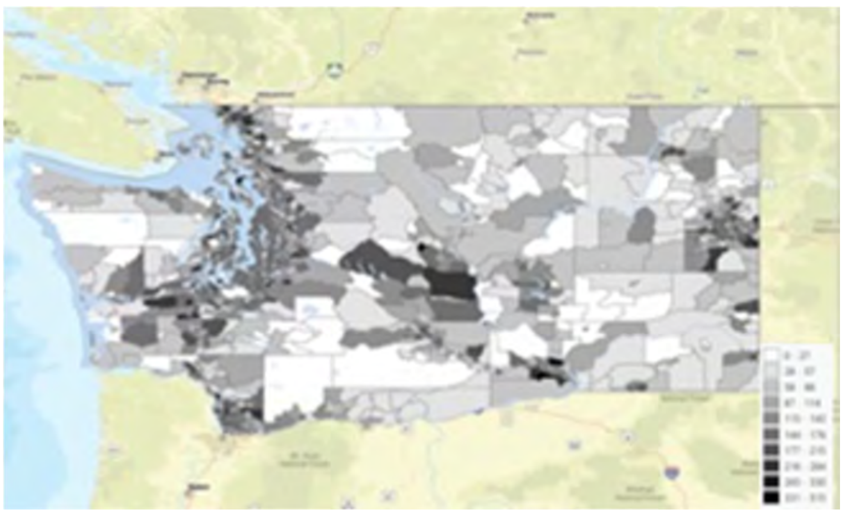
It is also possible to see that both lower- and higher-income households are spread throughout the Puget Sound region. Pockets of all income groups live within the typical travel sheds of all five toll facilities. While the fractions of lower- versus higher-income households vary considerably among the travel sheds, all five toll facilities affect travelers with lower incomes.



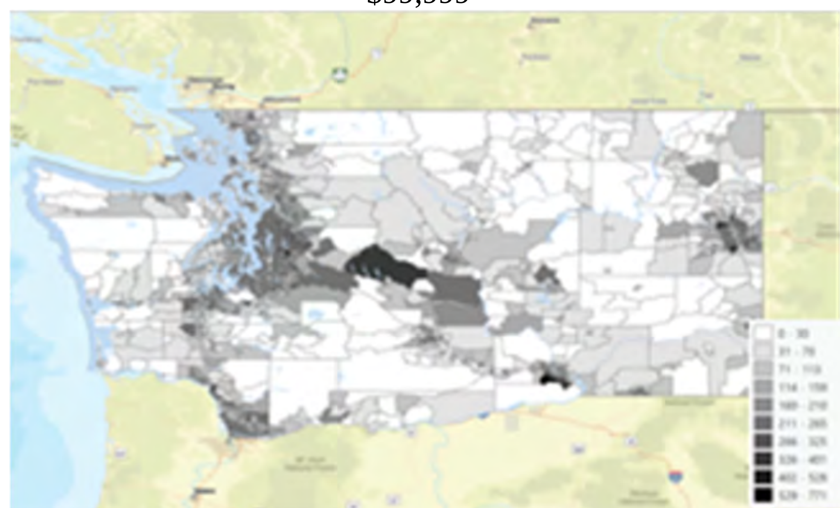
A) Number of Households with Income up to $49,999



B) Number of Households with Income from $50,000 to $99,999



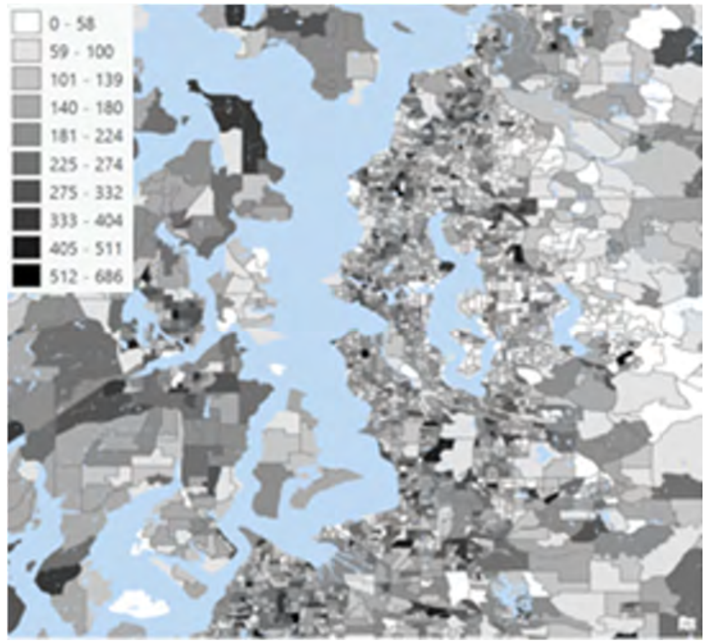
C) Number of Households with Income from $100,000 to $149,999



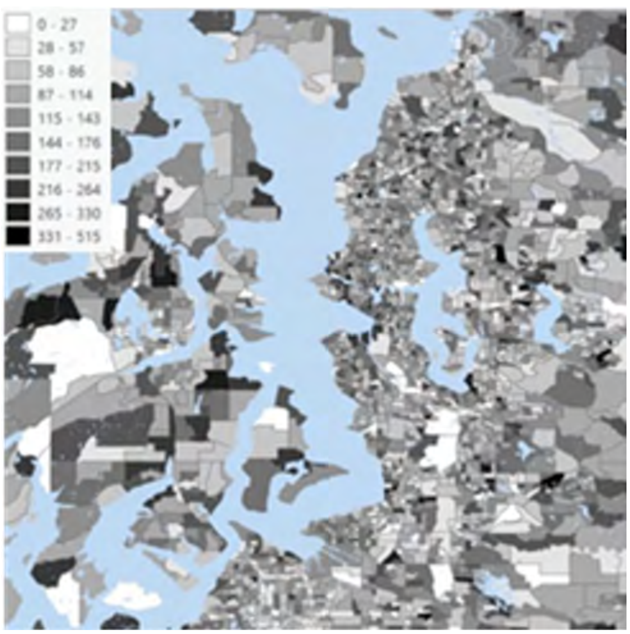
D) Number of Households with Income Above $150,000

Figure 2: Distribution of Households by Income Across Washington State

A) Number of Households with Income up to $49,999



B) Number of Households with Income from $50,000 to $99,999



C) Number of Households with Income from $100,000 to $149,999

D) Number of Households with Income Above $150,000

Figure 3: Distribution of Households by Income in the Puget Sound Region

Given the above distributions of incomes within the state and Puget Sound, it is useful to examine the concentration of accounts[9] that utilized the toll facilities at least once between July 2021 and June 2022. Figure 4 shows the total number of accounts for the entire state. Figure 5 shows a zoomed in view of the number of accounts per CBG in the Central Puget Sound region. In these graphics, an “account” includes both Good To Go! toll accounts maintained with WSDOT and the registered addresses associated with license plates billed when those vehicles used at least one of the WSDOT toll facilities but did not have a Good To Go! account.

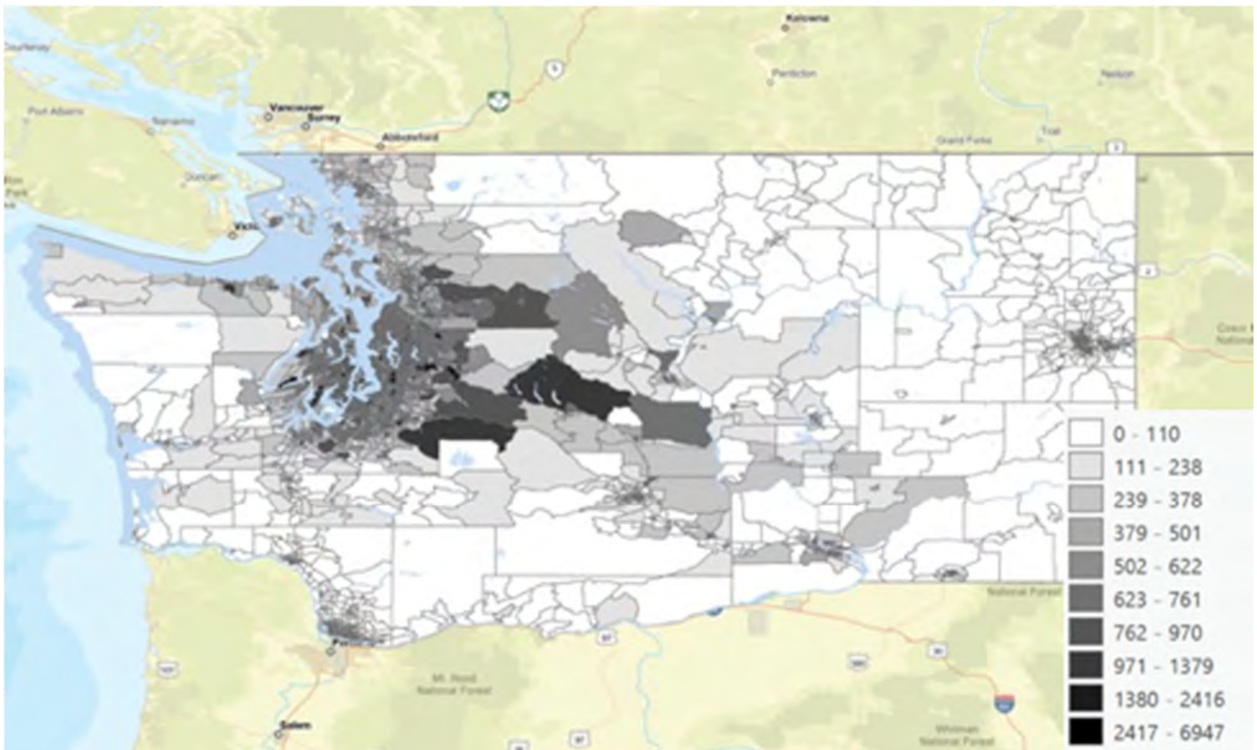


Figure 4: Total Toll Accounts for Each CBG Across the State

Figure 4 shows some important trends. Unsurprisingly, the number of accounts located in the eastern half of the state is low. This is due to the fact that all of the toll facilities are located in the western half of the state, thereby making it unlikely that residents in those households would make trips on one of the toll facilities. Therefore, all remaining figures that depict the use of each individual facility focus on the Central Puget Sound area. This means that not all trips are shown; however, the number of trips missing from the graphics is relatively small. One important note

[9] “Accounts” is a reasonable surrogate for “households that use one or more toll facilities.” Many accounts are associated with more than one registered vehicle. In these cases, the household account was counted only once.

about these trips from Eastern Washington not shown is that they include a higher proportion of trips by low frequency users (only one or two uses over the year) of the toll facilities. Some of these are lower-income households. This intuitively makes sense, as people from outside the metro area are likely to need to make only one or two trips across the tolled road network during the year and are less likely to understand the alternative routes they could use to avoid the tolls. Additionally, they may also be more reliant on routing services such as Google Maps, which are likely to route those users across toll facilities because of the calculated time savings. Generally speaking, most of these trips from the eastern portion of the state use either the I-405 Express Toll Lanes or the SR 520 bridge. This intuitively makes sense, as these are the facilities most easily accessible from the primary route across the mountains (I-90) and serve as useful time saving options for significant destinations in the Puget Sound region for those arriving from Eastern Washington via I-90.

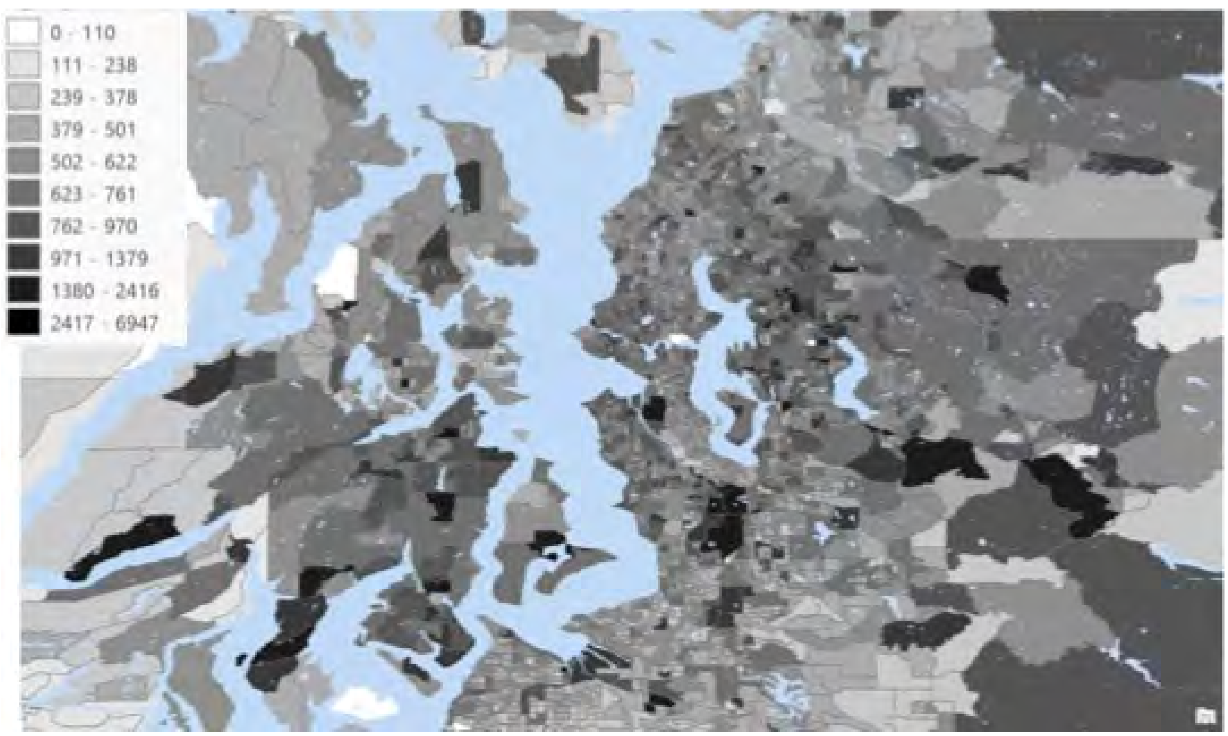


Figure 5: Total Toll Accounts for Each CBG In the Central Puget Sound Region

Overall, the general distribution of household income and toll accounts is about what one would expect for the state of Washington, with denser concentrations of accounts in CBGs that are close to the five toll facilities and decreasing numbers of accounts for those CBGs farther from the toll facilities. Multiple CBGs with large numbers of accounts are noticeably centered around the SR 167 toll facility and on the Kitsap peninsula, north of the Tacoma Narrows bridge. One somewhat surprising geographic area with a high number of accounts is centered on I-90, east and southeast of Issaquah. Those correspond to the same movements that Eastern Washington accounts make using I-405 and SR 520, as those routes serve trips to and from Issaquah and the significant activity mentioned above.

With the above general overview in mind, the next portion of this report examines the use and users of the individual toll facilities.

I-405

Figure 6 shows the number of trips that used the I-405 Express Toll Lanes by household location between July 2021 and June 2022. The I-5/I-405 corridor connects residents of the northern Puget Sound communities and the major eastside activity centers. Therefore, the primary movement on the Express Toll Lanes is between the residential communities along and north of the corridor and the activity centers (work and play) in the Bellevue area. Of course, this trip making is supplemented by modest amounts of reverse commute traffic and long-haul traffic (e.g., trips ending/beginning south of central Bellevue or east out I-90).

Once on I-405, these motorists can choose between I-405's general purpose (GP) lanes and the Express Toll Lanes, based on many factors, including each motorist's value of time and reliability at the time they are using the facility. Alternative routes for these travelers (mostly I-5 to I-90 or I-5 to SR 520) frequently take longer than using I-405.

Figure 7 shows the geographic areas where the majority of I-405 Express Toll Lane users reside and the income distributions of those CBGs. Figure 8 shows a different version of the data shown in Figure 7; it is based on a constant scale for the number of households in each category of CBG, whereas Figure 7 uses the Jenks Scale method.

Figure 7 and 8 demonstrate that the income levels of I-405 Express Toll Lane users generally follow the greater income trends of the region, with a higher number of lower-income users found in the north geographic area closer to Everett and farther from Bellevue and the Eastside communities. However, as is particularly evident in Figure 8, there are large numbers of relatively wealthy households in the corridor. These higher-income users tend to be concentrated in the center of the corridor and in Bellevue.

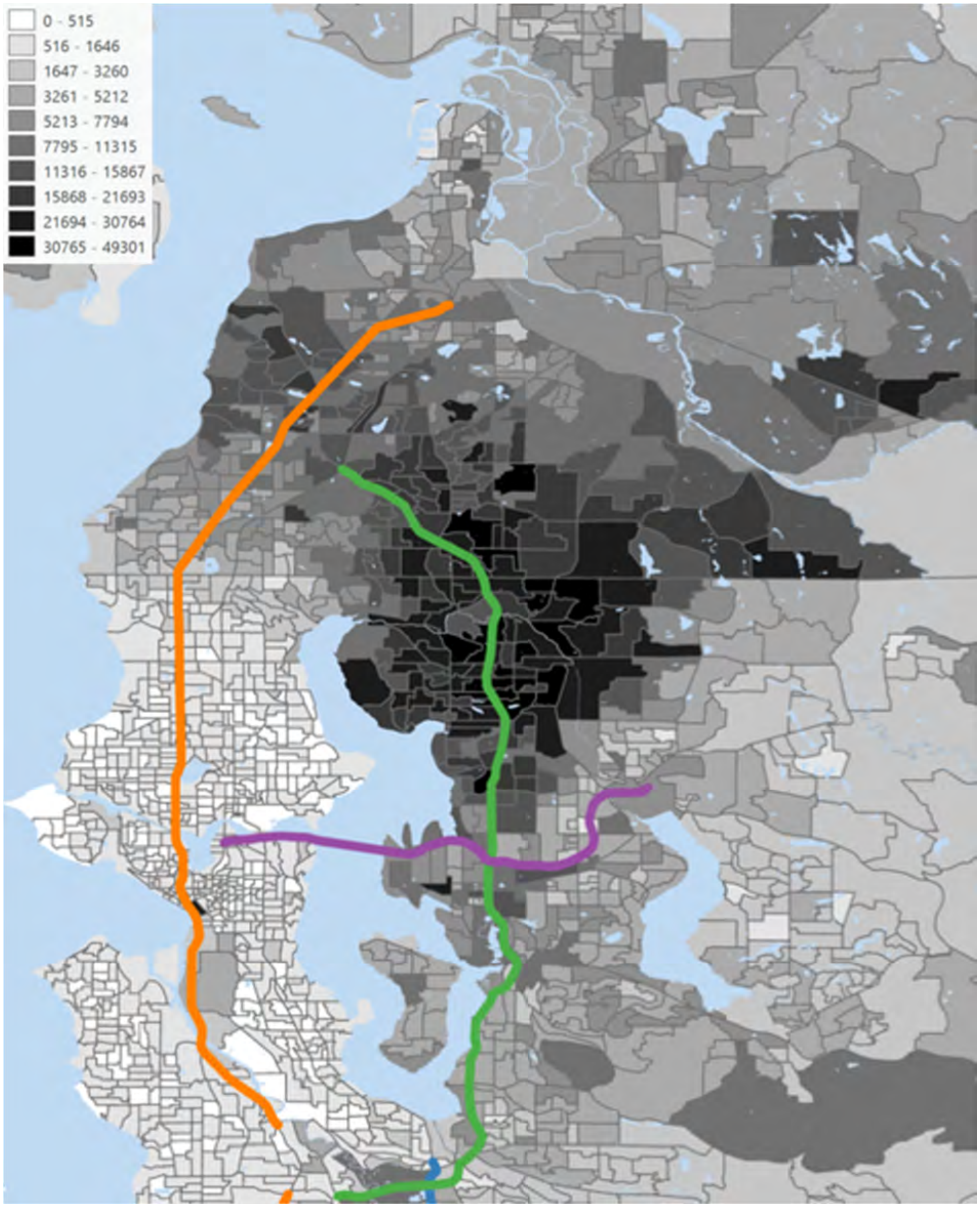
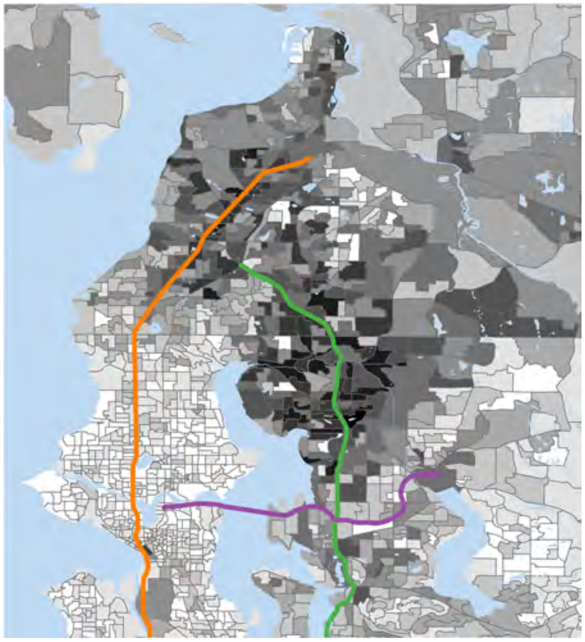
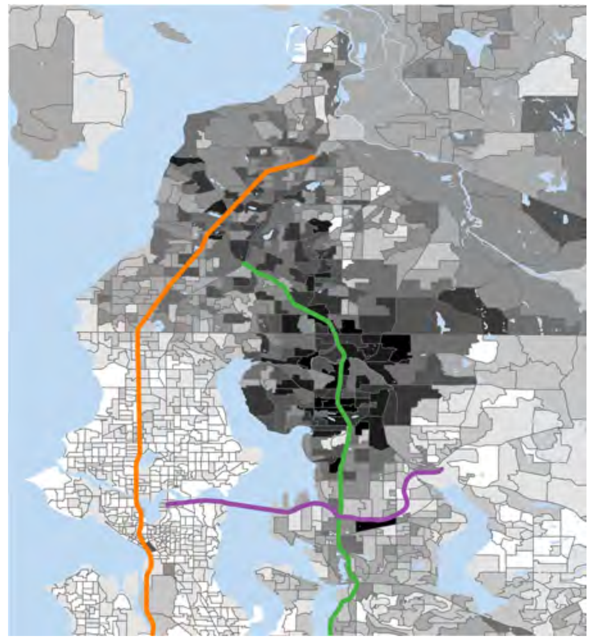


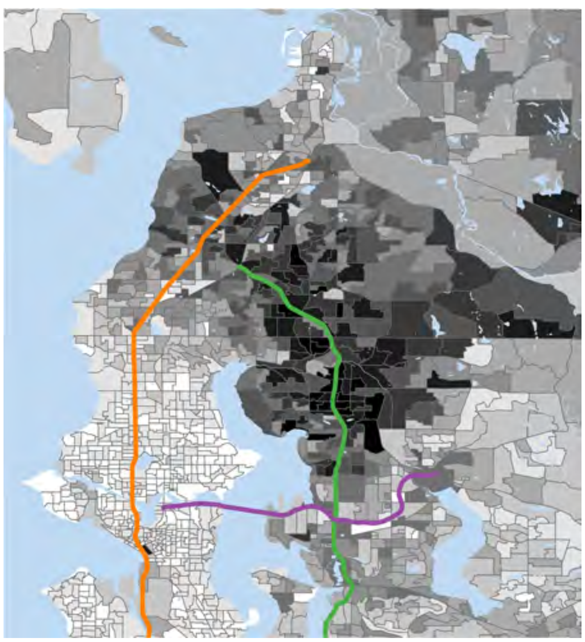
Figure 6: Number of Trips Taken on the I-405 ETLs from Each CBG



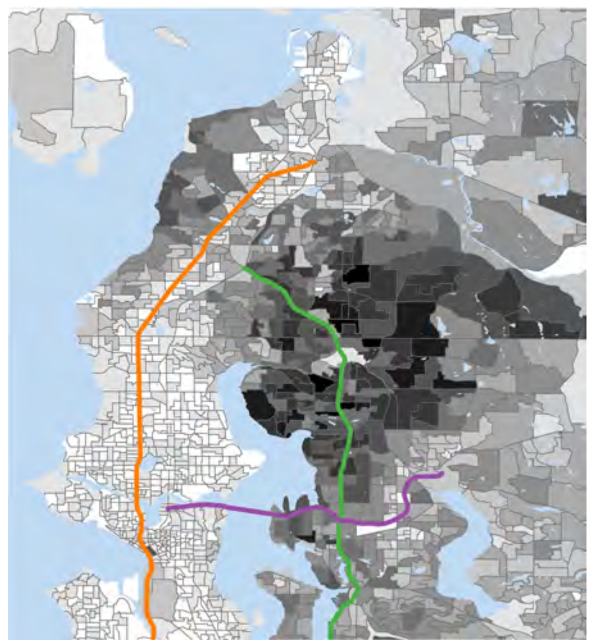
A) Number of Households with Income up to $49,999



B) Number of Households with Income from $50,000 to $99,999

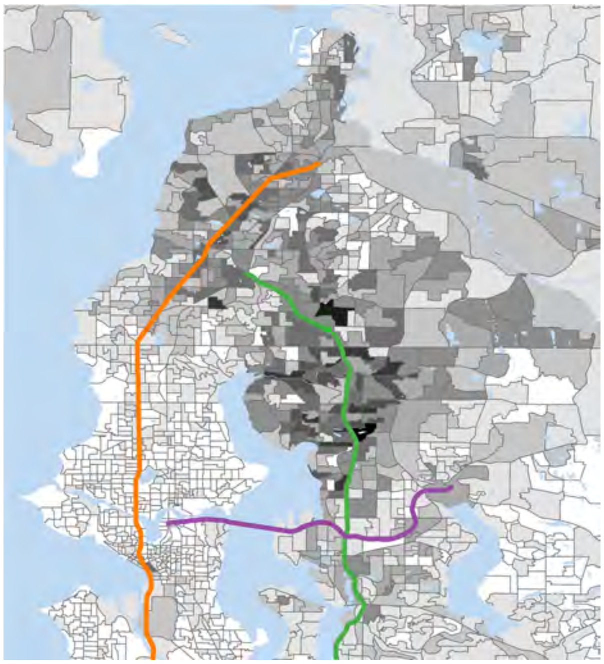


C) Number of Households with Income from $100,000 to $149,999



D) Number of Households with Income Above $150,000

Figure 7: Income Quadrants for Trips Taken on the I-405 ETLs from Each CBG



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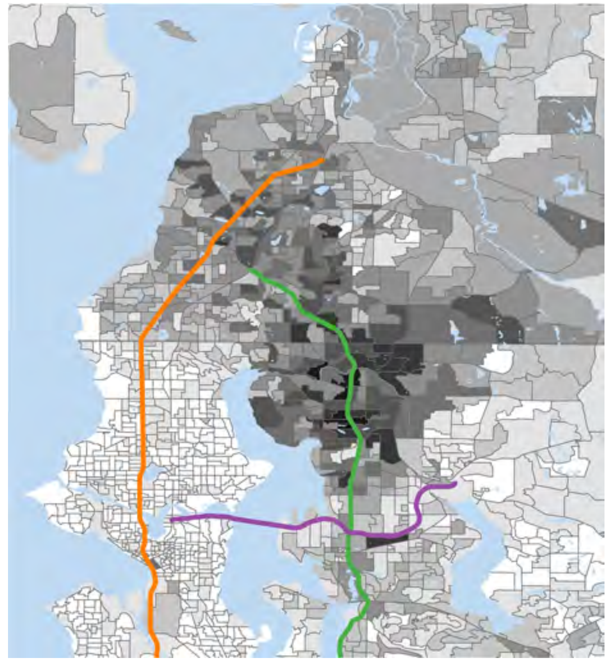

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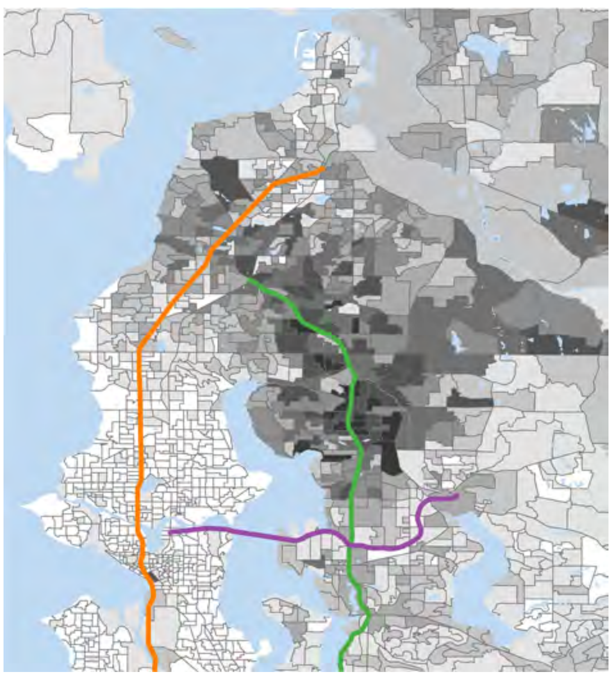
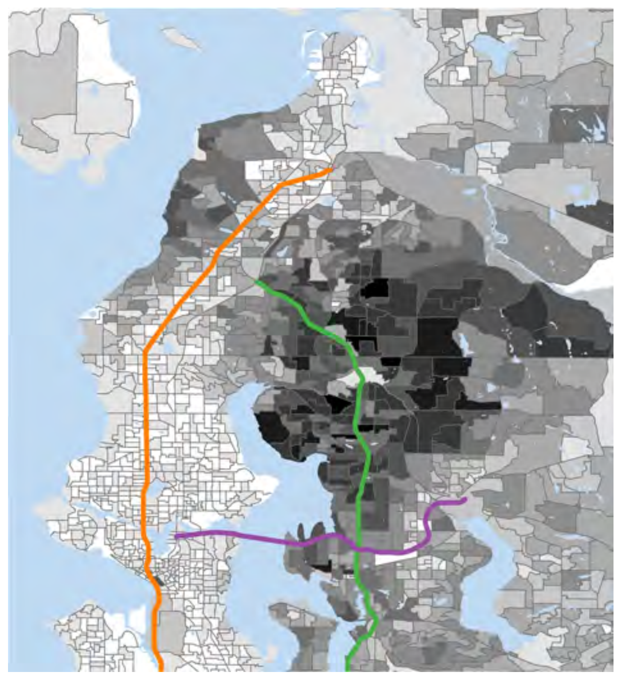


C) Number of Households with Income from $100,000 to $149,999



D) Number of Households with Income Above $150,000

Figure 8: Income Quadrants for Trips Taken on the I-405 ETLs from Each CBG with Fixed Scales

Figure 9 shows the income distribution of users of I-405 without the geographic overlay. In this figure, WSDOT toll transaction data (the grey bars) provide the income distribution for HOT lane users, and the CS LBS data (the blue bar)[10] are the basis for the income distribution of users of I-405 as a whole (i.e., the LBS data contain both HOT lane and GP lane users). The data are presented as the fraction of all trips made by households within the stated income categories.

Figure 9 shows that higher-income households are over-represented in both the "total users of I-405" and "just users of the HOT lane" relative to the four-county regional profile (the yellow bar). This is partly because the travel shed for I-405 skews to higher-income areas and partly because higher-income households typically make more vehicle trips than lower-income households. The comparison of total use of the facility versus WSDOT toll payment users shows that above an annual household income of $125,000, the HOT lane users skew even wealthier than I-405 as a whole. That is, the highest income users, who already make more trips on I-405, are even more likely to use the HOT lane when using the facility.

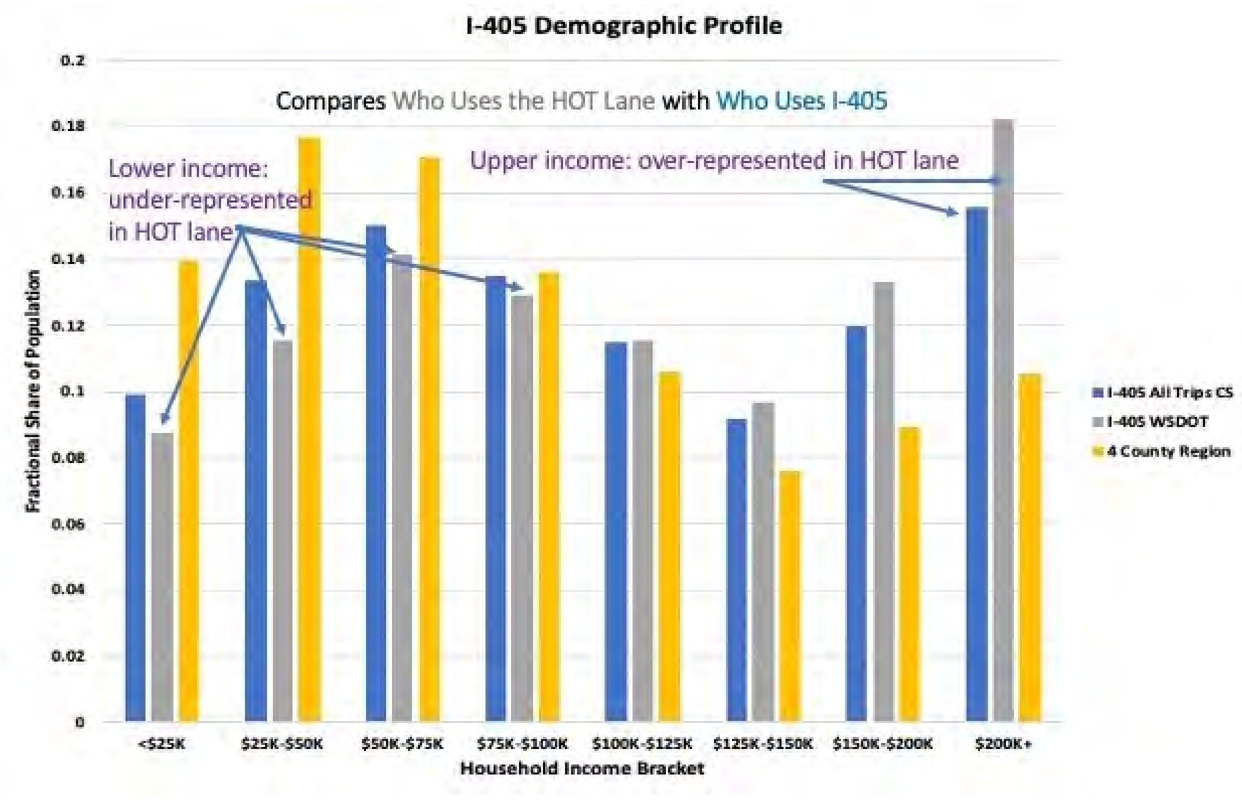


Figure 9: Income Profile of I-405 Users

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[10] The Cambridge Systematics LBS data are not able to differentiate HOT lane users from GP lane users, so it is not possible to separate out just those users of the GP lanes.

SR 520

Figure 10 shows the number of trips made across the SR 520 floating toll bridge based on the locations of the accounts' registered addresses. This figure clearly shows the unsurprising domination of home addresses along the SR 520 corridor for SR 520 trips. This makes sense, as people living in these areas will gain the most time savings when crossing Lake Washington because otherwise they must spend additional time detouring either north to SR 522 or I-5 to travel north around the lake or south to I-90. Figure 11 shows the geographic distributions by income for SR 520 users calculated with the Jenks method, and Figure 12 shows the geographic distributions calculated with fixed numeric categories.

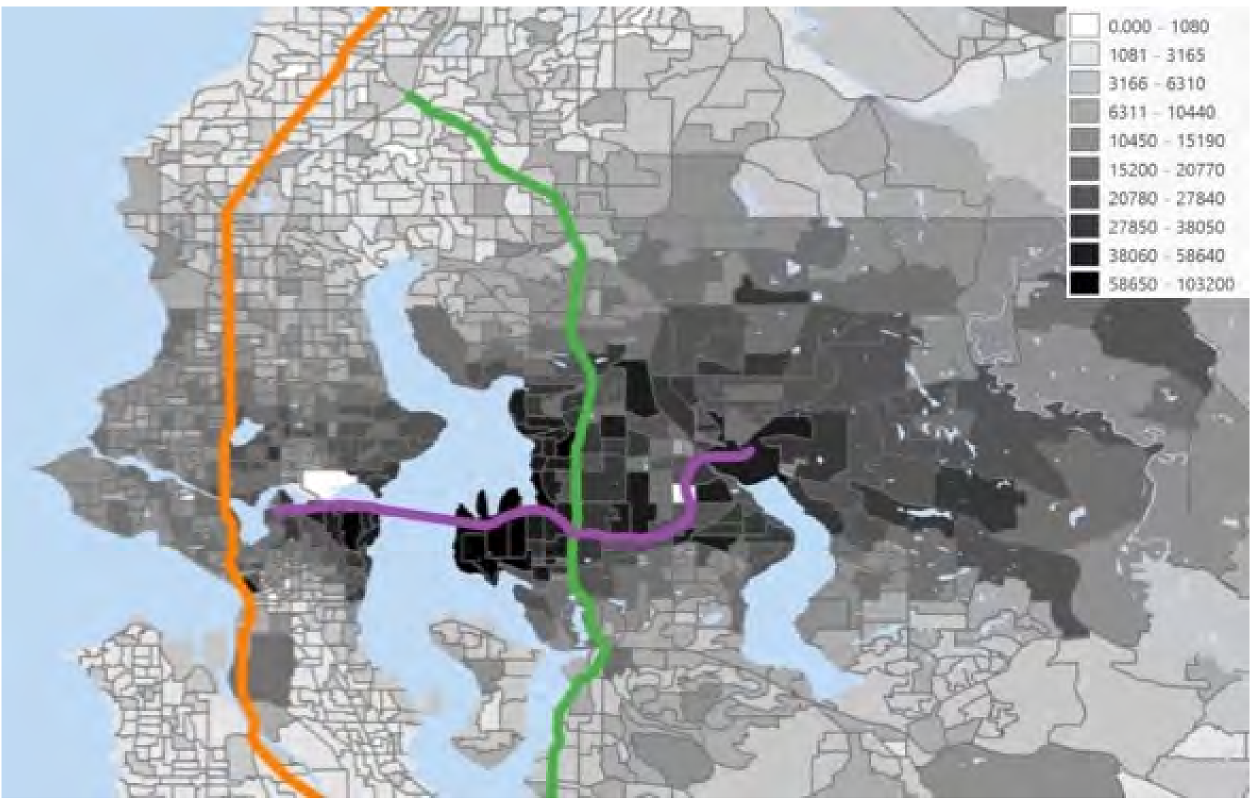


Figure 10: Number of Trips Taken on the SR 520 Toll Bridge from Each CBG

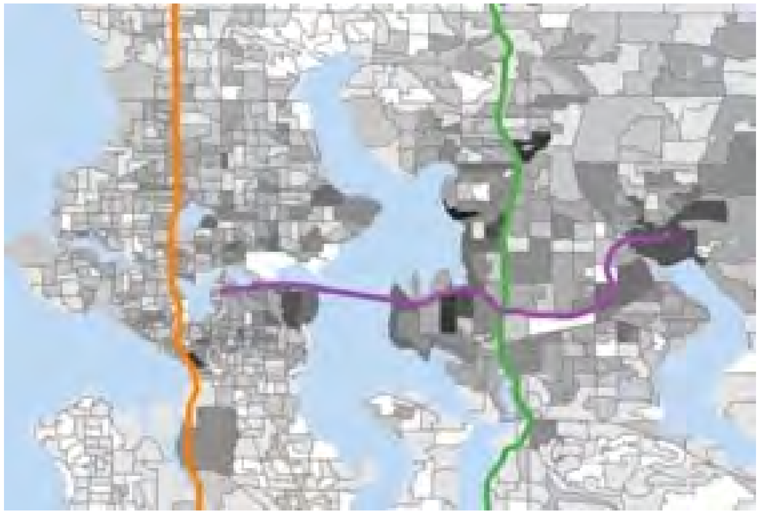
A) Number of Households with Income up to $49,999

B) Number of Households with Income from $50,000 to $99,999

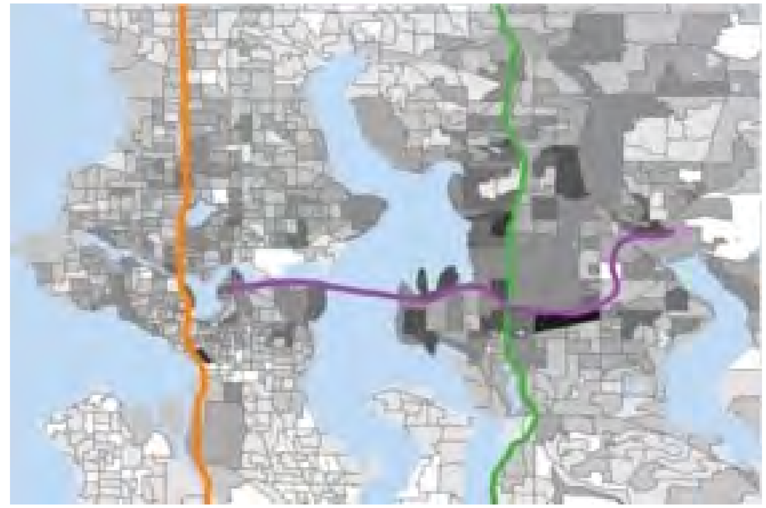
C) Number of Households with Income from $100,000 to $149,999

D) Number of Households with Income Above $150,000

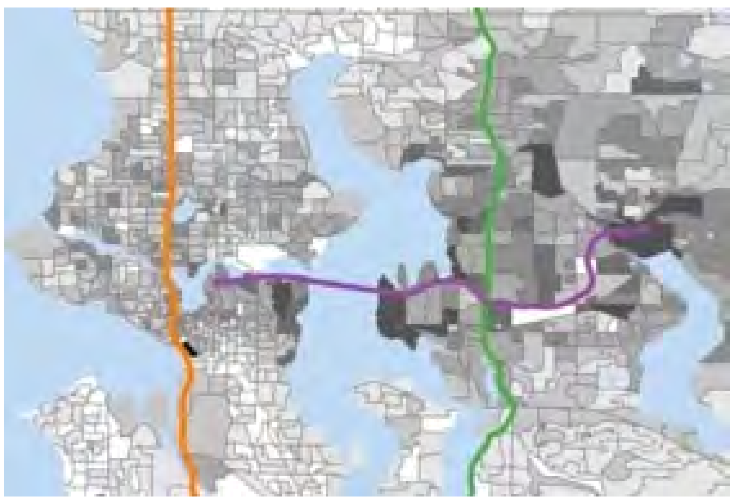
Figure 11: Income Quadrants for Trips Taken on the SR 520 Toll Bridge from Each CBG



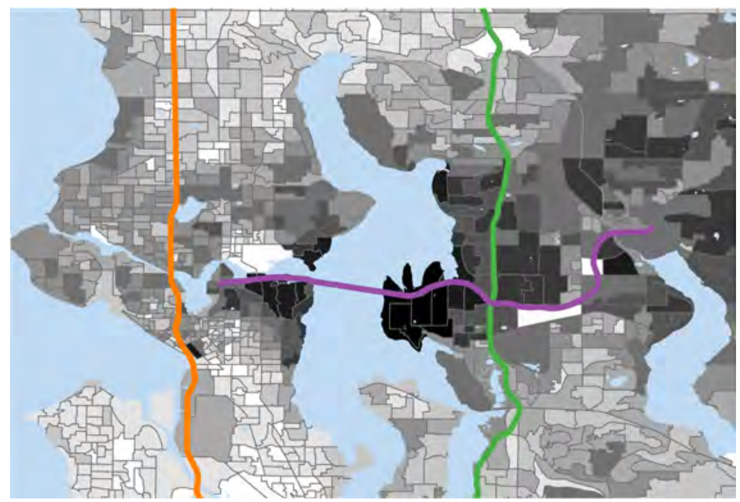
A) Number of Households with Income up to $49,999



B) Number of Households with Income from $50,000 to $99,999



C) Number of Households with Income from $100,000 to $149,999



D) Number of Households with Income Above $150,000

Figure 12: Income Quadrants for Trips Taken on the SR 520 Toll Bridge from Each CBG with Fixed Income Scales

Figure 12 shows the apparent skew toward high-income households found on this corridor, with many of the CBGs along the SR 520 corridor having large numbers of high- and moderately high-income households. SR 520 bisects and connects some of the wealthiest parts of the region. This is especially evident for the highest income category. There is a high concentration of trips from areas right next to Lake Washington, even on the west side of the lake, as a large number of trips across the lake originate from high income areas of Capitol Hill, Montlake, and the Madison Valley.

The skew on SR 520 toward high-income users is even more apparent in Figure 13, which removes the geographic element of the distribution.

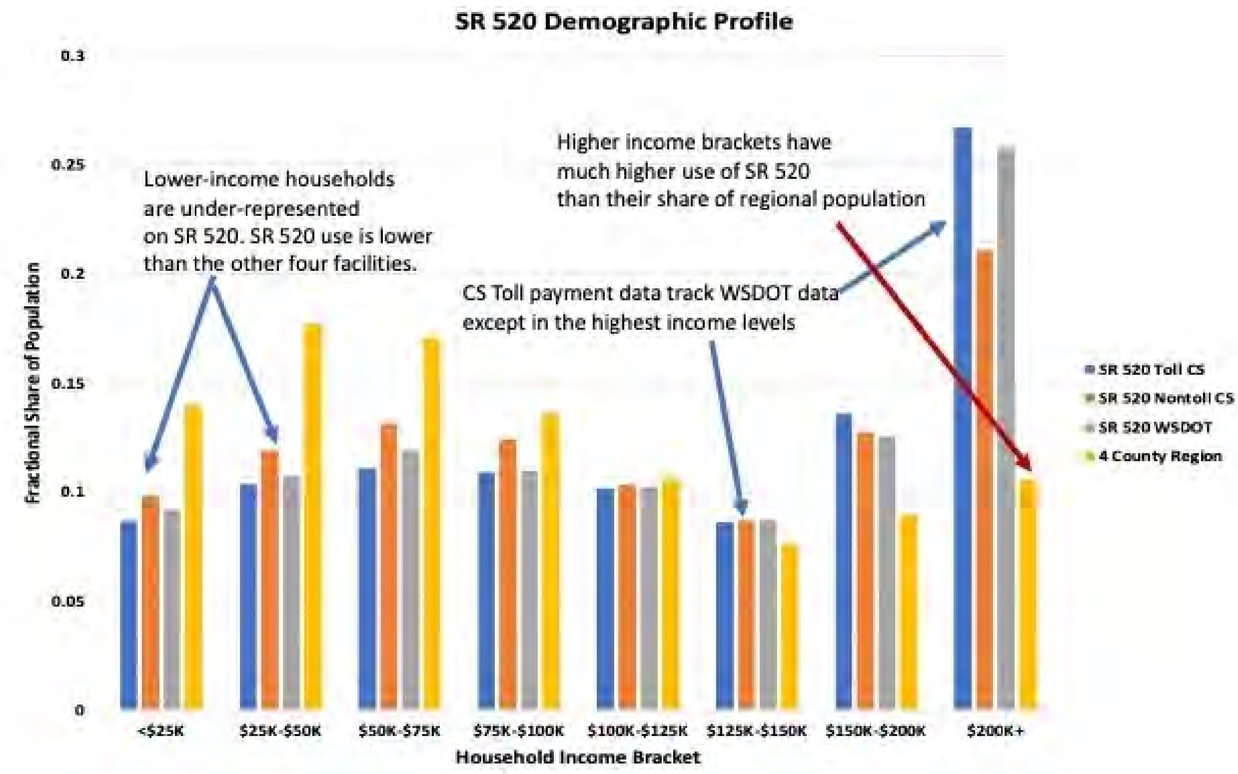


Figure 13: Income Profile of SR 520 Users

Unlike Figure 9, Figure 13 has four columns. The fourth column describes the income distribution of households that make trips that do not use SR 520 but have origins/destinations similar to trips that do use SR 520. These trips either use I-90 or go around north of the lake. This fourth column in the chart allows comparison of the income distributions of travelers who decline to pay to use SR 520 but still need to cross the lake.

What is apparent in Figure 13 is the very high over-representation of high-income groups that pay to use the bridge relative to the regional income distribution. This is partly because the corridor is bordered by many higher-income household neighborhoods, and partly because there are rational, non-toll travel options for people who wish to avoid the toll (SR 522 or southbound I-5 to the north, I-90 to the south). There is also very good transit service from the eastside to major Seattle destinations.

Figure 13 shows that lower- and moderate-income households make up a larger fraction of non-toll trips than higher-income households. The differences between toll paying trip behavior and toll avoiding behavior are modest for the lowest income categories, as these communities make modest numbers of trips across the lake. However, the differences between toll paying and toll avoiding increase up to the $100,000 annual household income level. At that point, the availability of higher household incomes causes the travel time advantages available by paying the SR 520 toll to outweigh the cost of the toll, and the share of households paying the toll increases. This trend increases substantially in the highest income bracket. Also apparent is the very high number of trips made across the lake by the highest income households. This is both because higher-income households typically make more trips and because of the large number of high-income households in the SR 520 travel shed.

Figure 14 results from using the LBS data to examine the number of trips for comparable origins and destination that cross Lake Washington, and it compares the number of trips that use SR 520 and pay a toll and the number that choose an alternative route and avoid paying that toll.[11] Given the added time required for many of the alternative travel paths in comparison to using SR 520, it is not surprising that even travelers from lower-income brackets take more trips over SR 520 than on the more circuitous routes. It is also clear that all income groups take alternative routes. What is very interesting is the increasing number of trips taken that use the bridge in comparison to the number that avoid paying a toll at the highest income brackets. The highest income brackets use SR 520 almost three times as often as non-toll routes. Some of this may simply be caused by the proximity of wealthier neighborhoods to SR 520, making use of alternatives more costly from a time perspective. However, there is definitely a trend for higher-income households to use the

[11] These statistics were computed by identifying which CBG origin/destination pairs produce trips across SR 520 and then using those O/D pairs to compute the total number of trips made from those O/D pairs both using SR 520 or not using SR 520.

toll facility more often and thus shoulder a larger share of the cost of the bridge. This is good from an equity perspective.

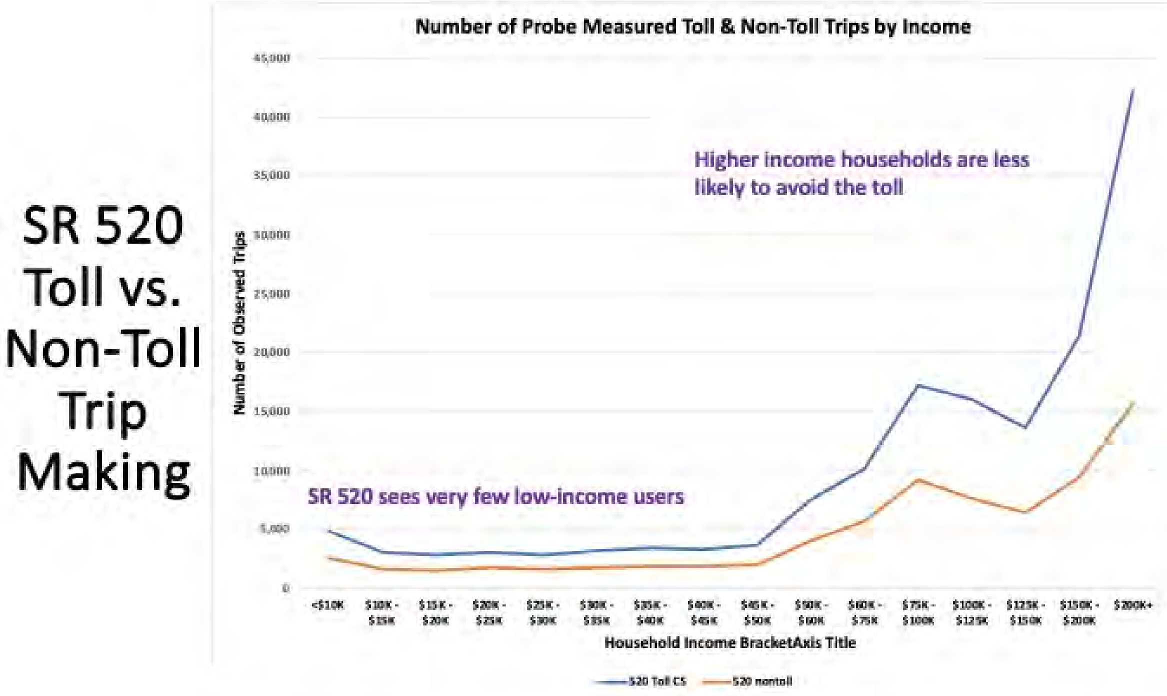


Figure 14: Comparison of SR 520 Toll Paying vs. Toll Avoiding Cross-Lake Trips

An additional observation is that the share of SR 520 travel described by the LBS data (blue bar) and the WSDOT toll data (grey bar) in Figure 13 tracks very well for most income groups, although LBS data slightly under-represent the lowest incomes groups and slightly over-represent the highest income groups. The slightly higher prediction of trips by the LBS data for the highest income groups is likely caused by the slight bias resulting from higher cellphone and application use by households in those income brackets.

<u>SR 167</u>

Figure 15 shows the trips made by accounts that used the SR 167 HOT lane facility. SR 167 has much lower use than I-405 or the other three toll facilities in this study. One of the results is that the scales for the CBG trip making are much lower (so a black CBG has fewer trips in Figure 15 than it does in either Figure 6 or Figure 10). However, the figures in this section still provide an excellent understanding of the relative importance of each geographic area in terms of its use of SR 167. Thus, it can be seen that many the toll accounts that use SR 167 are located south and east of the facility (e.g., Sumner and Puyallup). There seem to be several concentrations of low-income users along the facility, including at the north end near Renton and near downtown Kent. The accounts located in the Kent business district west of the facility are likely NOT household accounts but commercial accounts. These are likely associated with small businesses located in that portion of the valley.

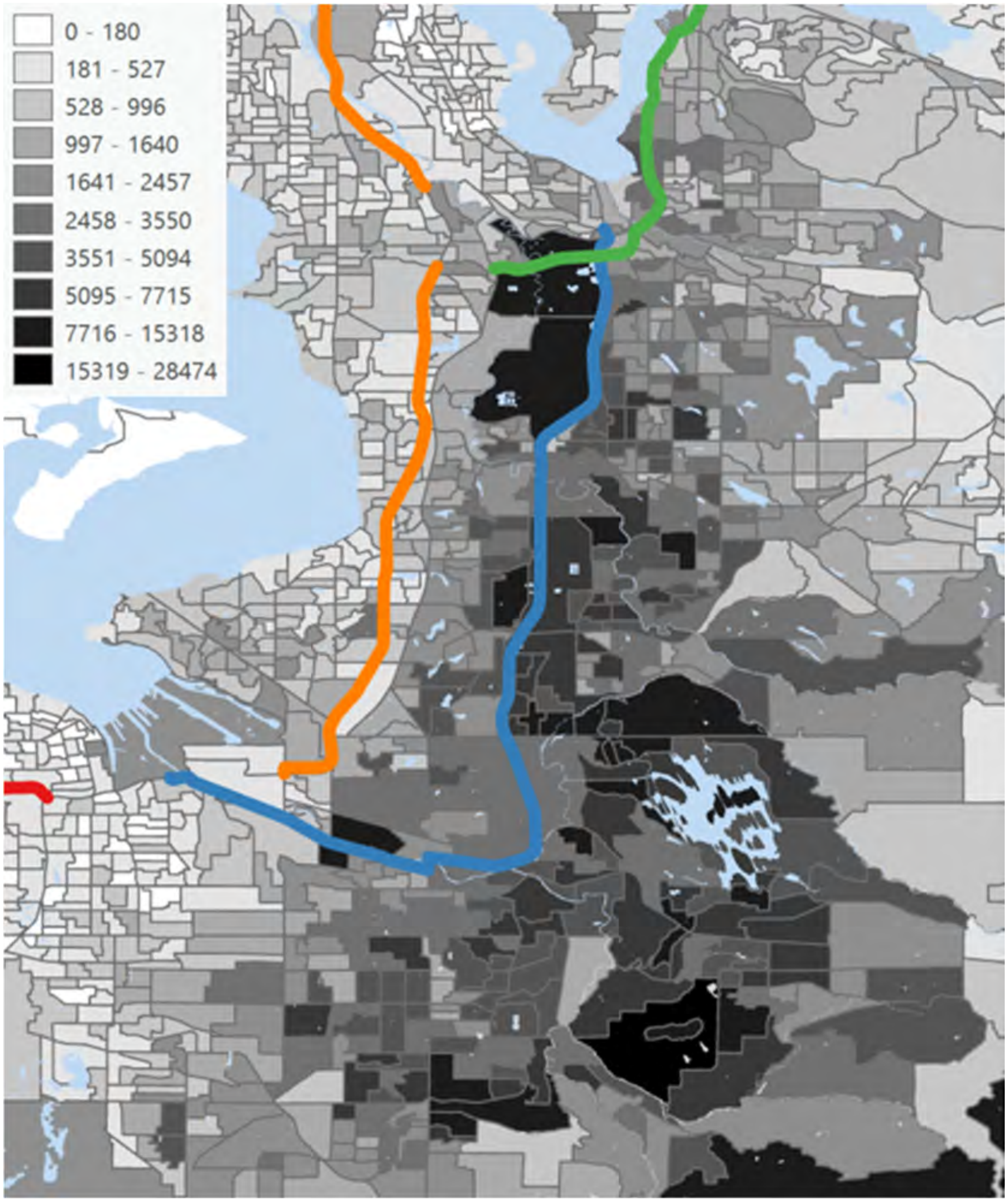
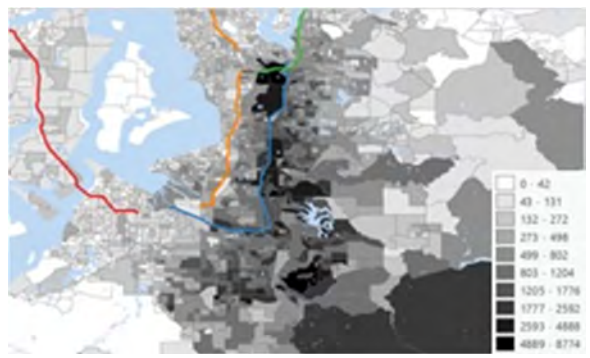


Figure 15: Trips Taken on the SR 167 HOT Lanes from Each CBG

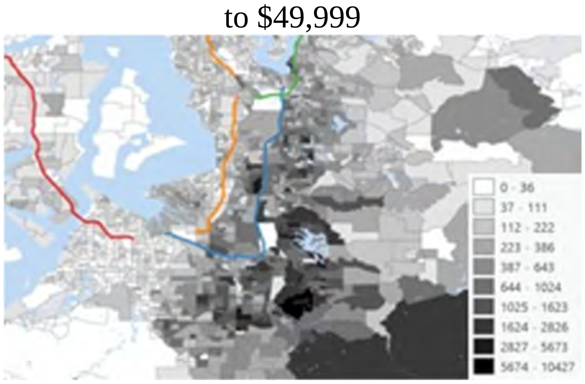
The residential household locations of these trips is concentrated in the central Green River Valley that SR 167 follows through the southern part of King County and the northern part of Pierce County. Importantly, use of SR 167 for households located west of I-5 is very low, indicating that few individuals who live west of I-5 use SR 167 as an alternative to this congested stretch of I-5. These same outcomes can be seen in Figure 16 and Figure 17, which show the geographic distributions of household trip making by income distribution for the SR 167 HOT lane.

Figure 16 (based on the Jenks method) and Figure 17 (based on fixed category scaling) show that households of all income strata are located throughout the SR 167 travel shed. That is, each income level is relatively evenly represented. SR 167 does have higher concentrations of low- and moderate-income households in comparison to I-405 and especially in comparison to SR 520.

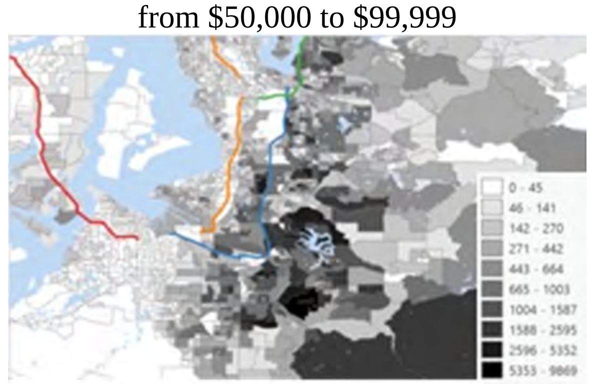
A) Number of Households with Income up to $49,999



B) Number of Households with Income from $50,000 to $99,999

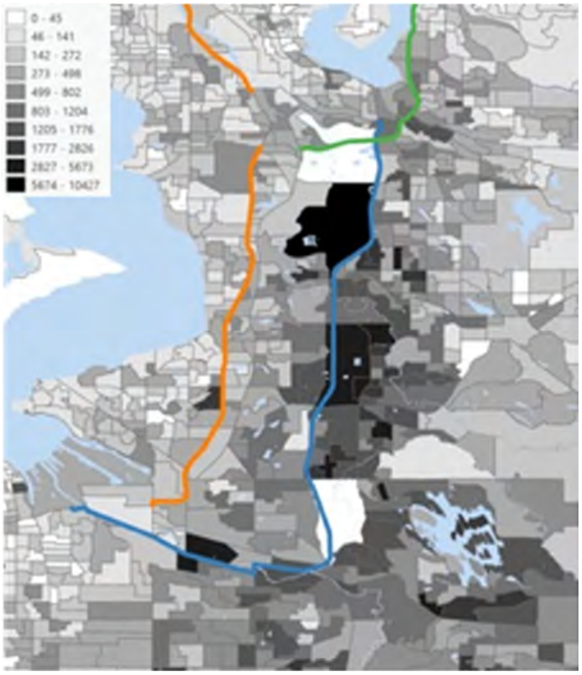


C) Number of Households with Income from $100,000 to $149,999

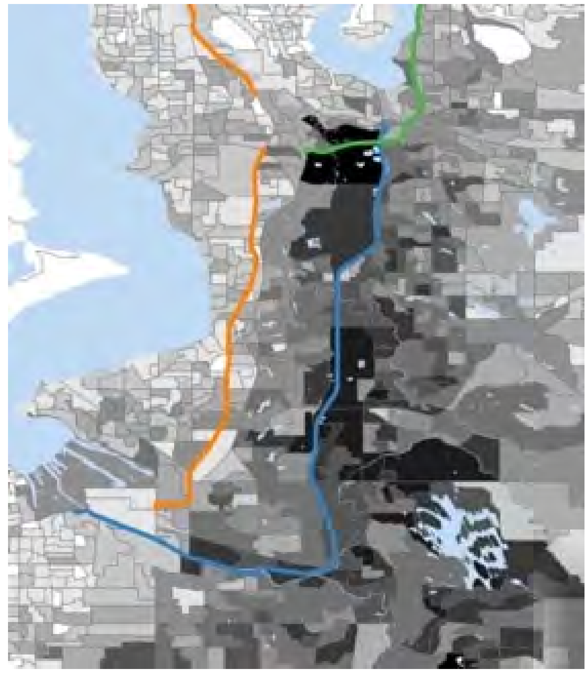


D) Number of Households with Income Above $150,000

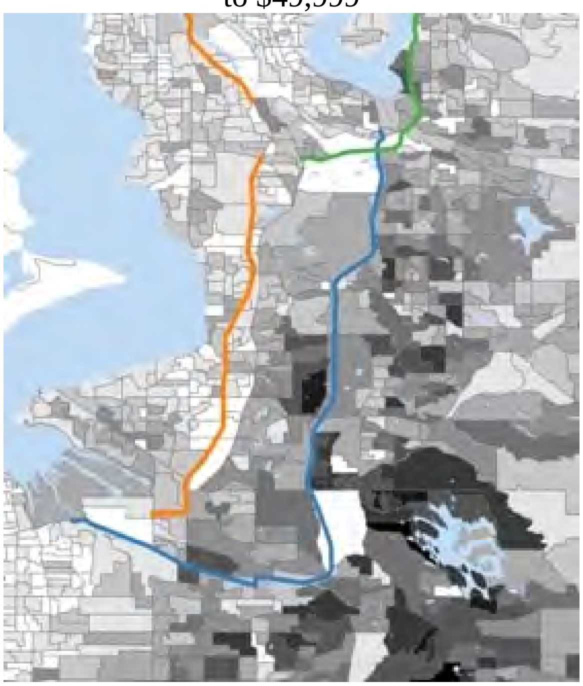
Figure 16: Income Quadrants for Trips Taken on the SR 167 HOT Lanes from Each CBG



A) Number of Households with Income up to $49,999



B) Number of Households with Income from $50,000 to $99,999



C) Number of Households with Income from $100,000 to $149,999

D) Number of Households with Income Above $150,000

Figure 17: Income Quadrants for Trips Taken on the SR 167 HOT Lanes with Fixed Income Scales

Figure 18 illustrates the overall income profile of users of the SR 167 HOT lane. It shows the relative fraction of users of the roadway by annual household income category. The figure shows that lower-income households are under-represented relative to their share of the regional population. But this under-representation is smaller than that on I-405 (see Figure 9). In addition, the difference between the profiles of all SR 167 users (those who use SR 167 regardless of whether they travel the GP or HOT lanes) and those who pay to use the HOT lanes is small in the lower-income categories. However, for middle-income brackets ($60,000 to $150,000 annual income), the fraction of the population that uses the HOT lane actually exceeds the fraction of all facility users, and both exceed that income group's share of the regional population. Surprisingly, this relationship flips at the higher-income levels. These households use the facility more than their share of the regional population but are a lower fraction of the toll paying population, and their use of the HOT lane is actually lower than expected given the regional population profile.

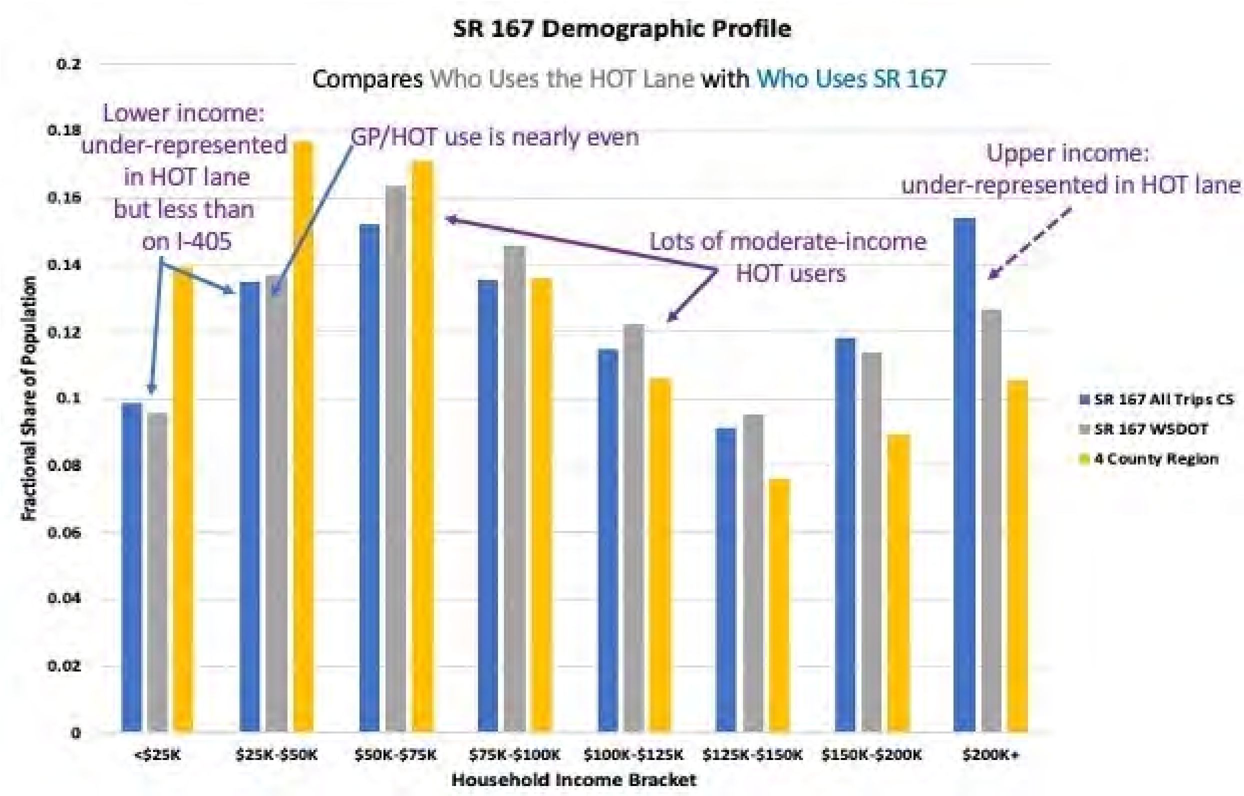


Figure 18: Income Profile for SR 167 Users

SR 99

Figure 19 shows the distribution of trips associated with accounts that use the SR 99 toll tunnel. Like all other facilities, the geographic distribution of the households that use the SR 99 tunnel is reflective of the service shed of the facility. The highest concentrations of use originate in Ballard, Freemont, North Seattle, the Duwamish Valley, and West Seattle. This was exactly the target population when the tunnel was designed and built (opened to the public in 2019).

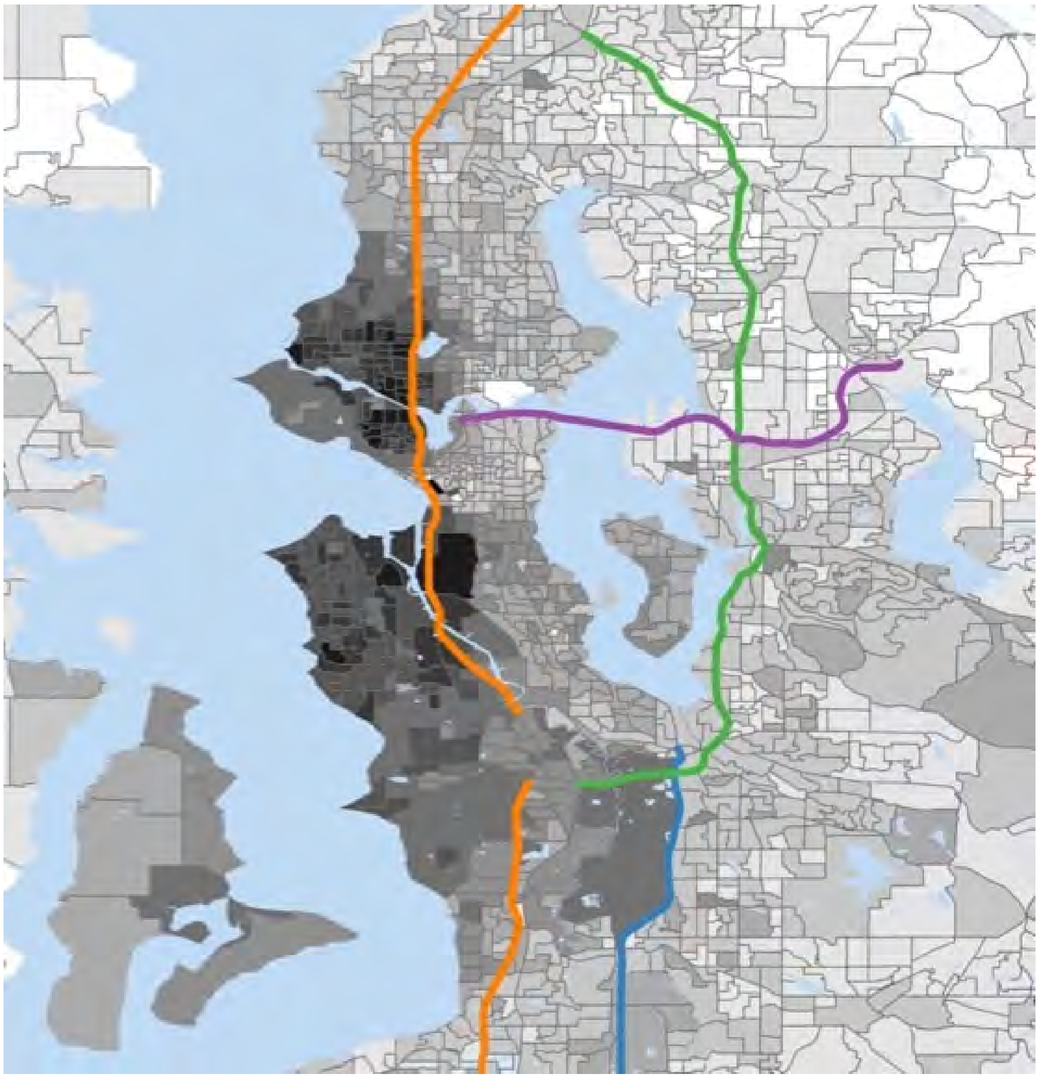
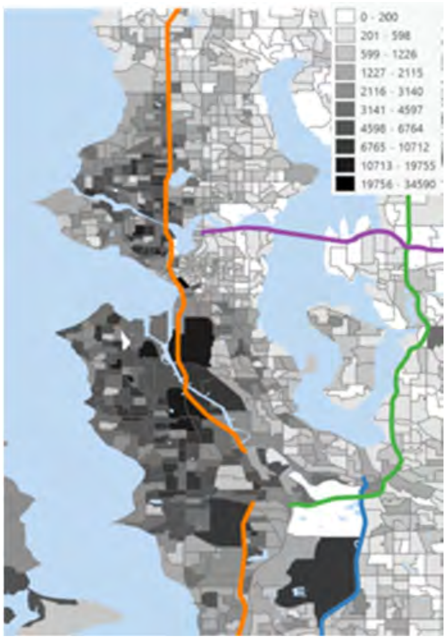


Figure 19: Trips Taken on the SR 99 Toll Tunnel from Each CBG

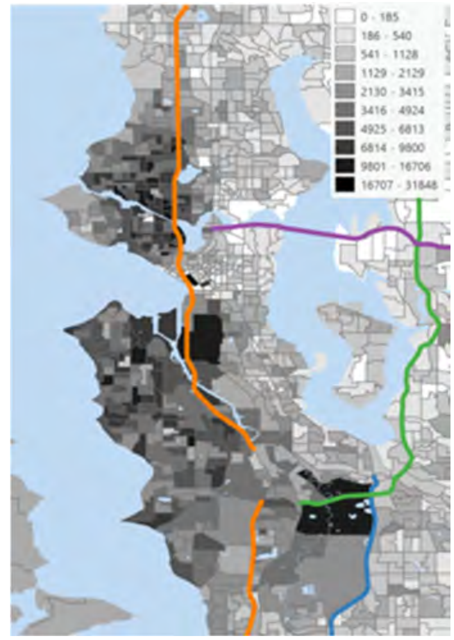
More modest trip making on SR 99 does originate from the northern and southern neighborhoods of Seattle, which can use SR 99 to bypass a congested I-5 or as an easy access to destinations of interest in Seattle (e.g., the sports stadiums south of downtown, the Seattle Center, Queen Anne, and Ballard). Other areas of the city are not highly represented because there are reasonable alternatives that, when uncongested, do not yield significant time penalties—usually I-

5 or local streets. This is similar to the reason that few people who live west of I-5 in southern King County use SR 167.

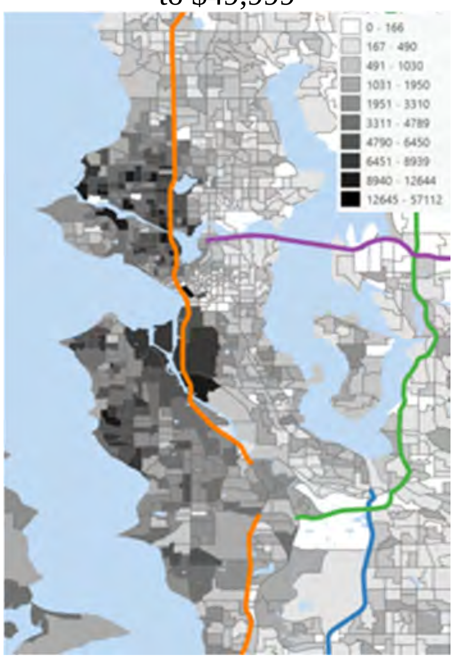
Figure 20 and 21 show the geographic distributions of household trip making on the SR 99 tunnel by income distribution.



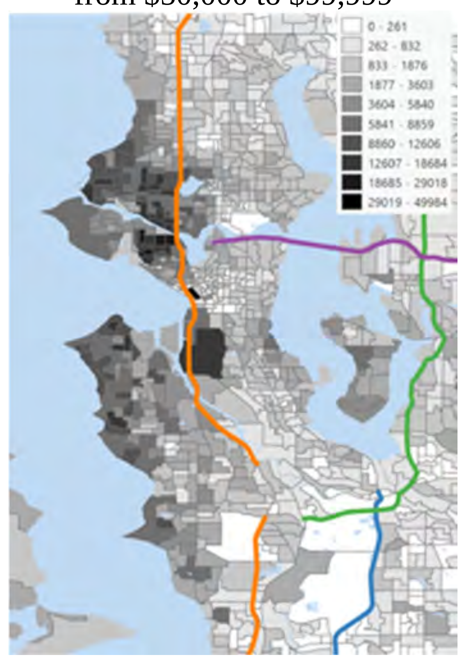
A) Number of Households with Income up to $49,999



B) Number of Households with Income from $50,000 to $99,999

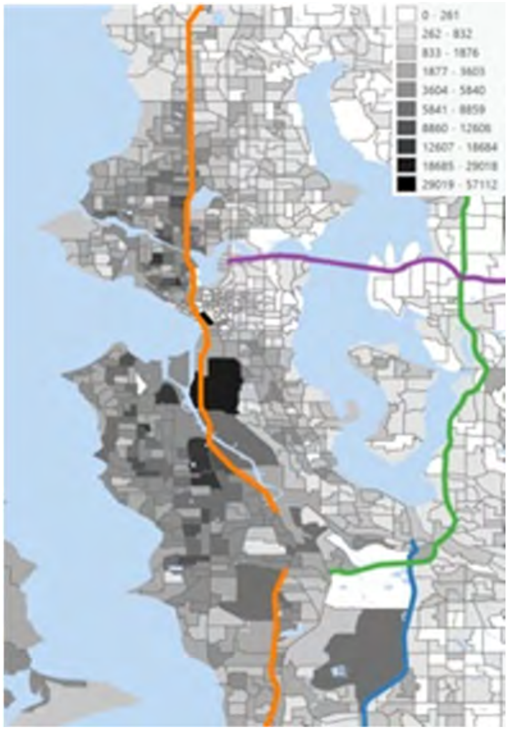


C) Number of Households with Income from $100,000 to $149,999



D) Number of Households with Income Above $150,000

Figure 20: Income Quadrants for Trips Taken on the SR 99 Toll Tunnel from Each CBG



A) Number of Households with Income up to $49,999

B) Number of Households with Income from $50,000 to $99,999

C) Number of Households with Income from $100,000 to $149,999

D) Number of Households with Income Above $150,000

Figure 21: Income Quadrants for Trips Taken on the SR 99 Toll Tunnel with Fixed Income Scales

The above figures show that the core areas of trip provision have fairly significant numbers of higher-income households, whereas the "supporting" neighborhoods typically have lower incomes. Figure 22 shows the income profile of motorists who use the SR 99 tunnel. This figure shows that the higher-income neighborhoods identified in the previous figures generate a substantial number of toll trips. Also, unusually, the LBS data do not over-represent this behavior relative to the WSDOT toll tags. In this case, the highest income bracket shows additional trips in the WSDOT dataset in comparison to the LBS data.

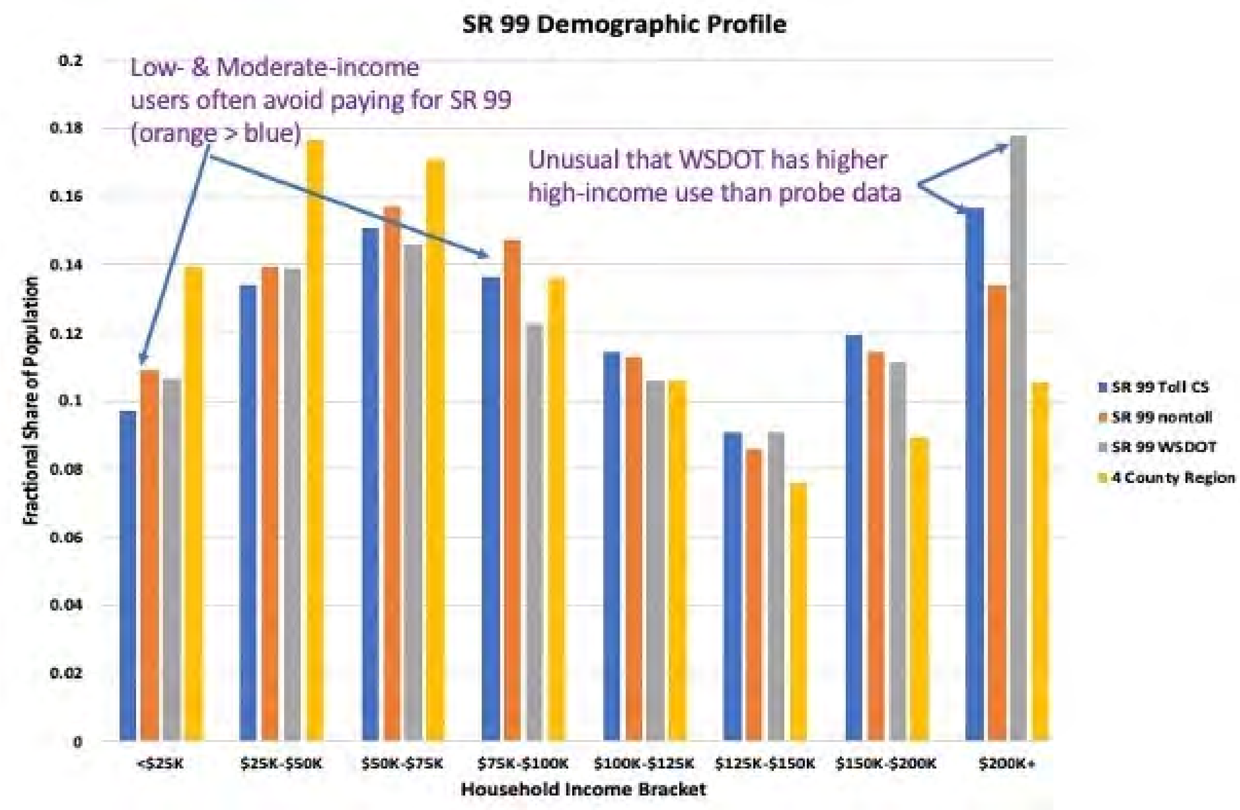


Figure 22: Income Profile for SR 99 Tunnel Users

Interestingly, this corridor follows the regional income distribution very closely, except at the very highest and lowest income brackets. This is true for both the LBS toll and no-toll datasets, as well as the WSDOT toll transaction dataset. The most notable break from the basic regional income distribution is the high number of low-income trips from the Duwamish Valley area in comparison to the other parts of the city. This does follow the income trends in the city, as these areas generally tend to have lower income overall. However, it is also possible that these trips are being taken by small businesses located in the industrial area south of downtown, where the businesses have only a few registered company vehicles and therefore are not identified as "businesses" by the constraint that required six vehicles per account to be identified as a business.

Figure 23 shows the number of toll paying trips made by household income category compared with the number of trips made between those same origins and destination but via routes that do not include the SR 99 tunnel. This figure shows that many of the trips made on SR 99 can be made via non-toll routes. For example, many users of SR 99 primarily use I-5 but shift to SR 99 when I-5 is badly congested, and SR 99 is not. This pattern of more non-toll trip making than toll trip making for similar O/Ds is true for all income brackets.

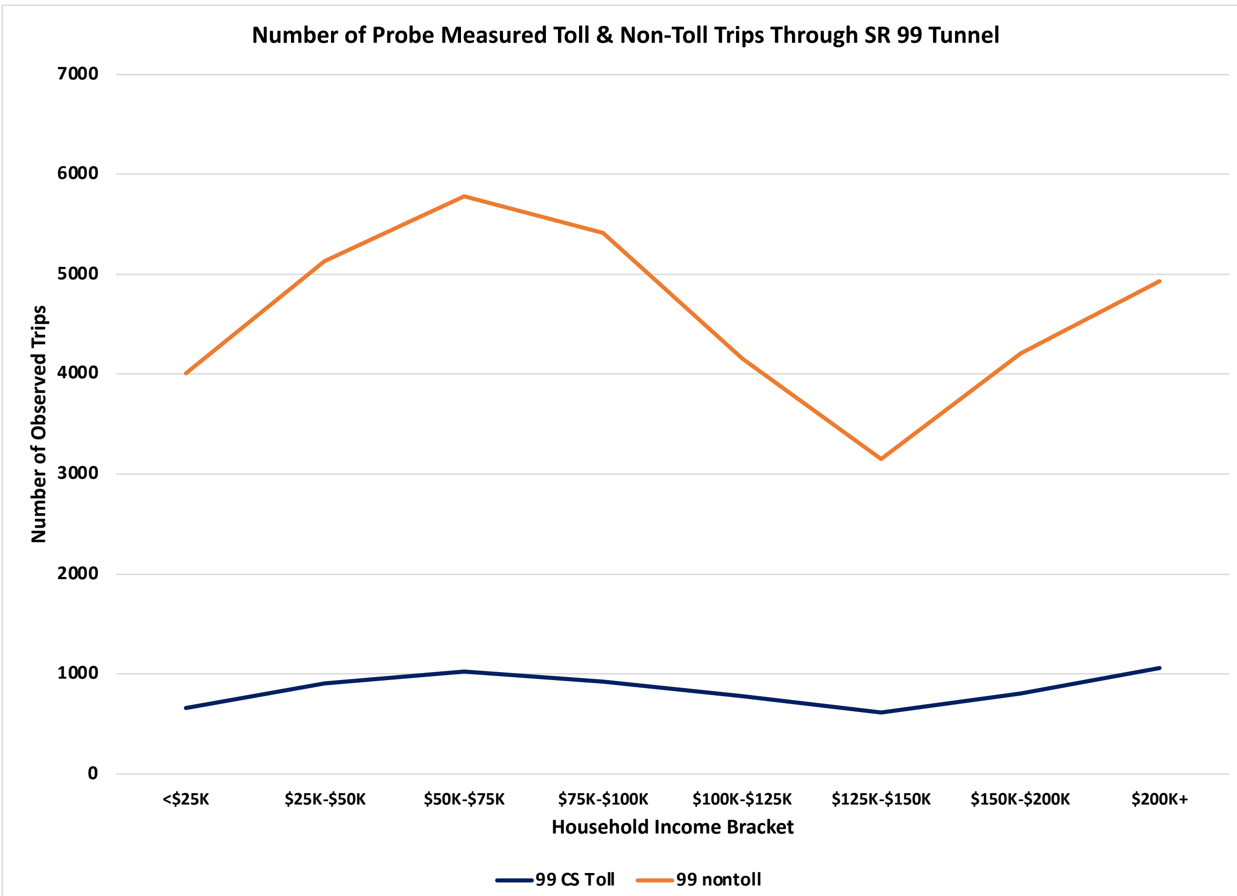


Figure 23: Comparison of SR 99 Toll Paying vs. Toll Avoiding Trips

Figure 24 shows the results when we take the data from Figure 23 and from Figure 14 and, instead of showing the number of toll paying and toll avoiding trips for comparable origins and destinations, show the fraction of trips made in these two categories by income group. This graphic shows that the toll avoidance rate on SR 99 is much higher than that on SR 520. This is because there are far more options for trips that are served by the SR 99 tunnel, whereas the alternatives for SR 520 are much fewer. The second major difference that stands out is that while higher-income households choose to make a higher percentage of tolled trips than lower-income households, the increase in that relationship is higher on SR 520 than on SR 99. On SR 520, the percentage increases from 64 percent in the $60,000 annual income bracket to 73 percent in the highest income bracket (+9 percent), whereas on SR 99 the increase is only from 15 percent to 18 percent.

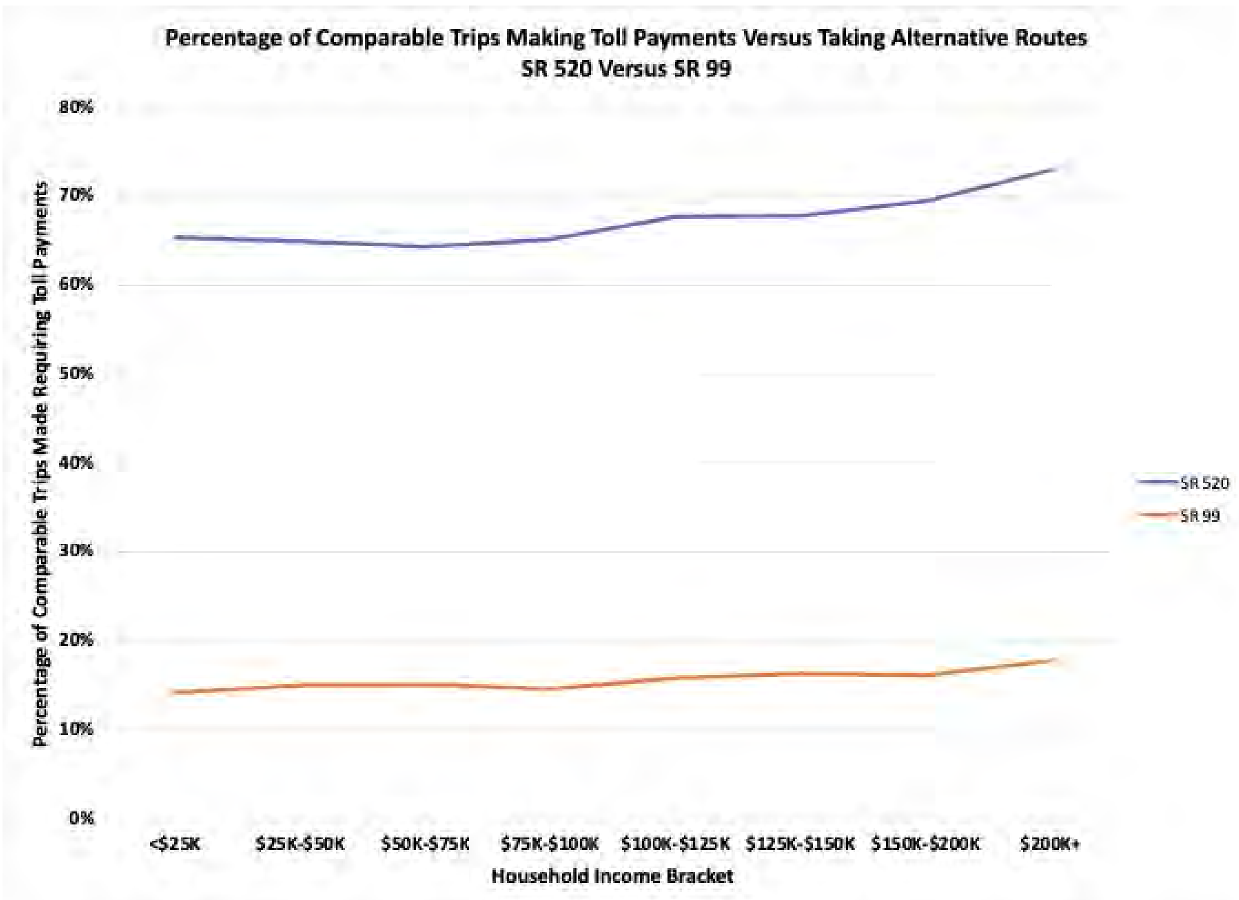


Figure 24: Comparing Toll Avoidance Rates for SR 520 and SR 99

Another interesting observation is that the rate of toll paying versus toll-avoiding trips is fairly constant across all income brackets, except for the highest income brackets. Toll avoidance is therefore assumed to be more a function of the availability of good alternatives, with most income brackets below the level of $75,000 annual income acting relatively similarly. Above $75,000, increases in income correlate to increases in willingness to pay tolls to obtain travel advantages, with the highest income brackets being most willing to pay tolls. However, the increasing rate at which tolls are paid, even at the highest income levels, appears to be heavily influenced by the travel benefits that can be obtained given route alternatives.

<u>SR 16</u>

Figure 25 shows the distribution of trips made across the Tacoma Narrows Toll Bridge on SR 16. Unsurprisingly, very high concentrations of these trips come from accounts located on the west side of the bridge on the Kitsap peninsula. This follows the widely accepted use pattern for the facility: that primarily residents of Kitsap County use it to access Tacoma, with a smaller portion of users originating south of the bridge in Pierce County or other eastern counties, all of which are supplemented by large numbers of infrequent users from the rest of the state.

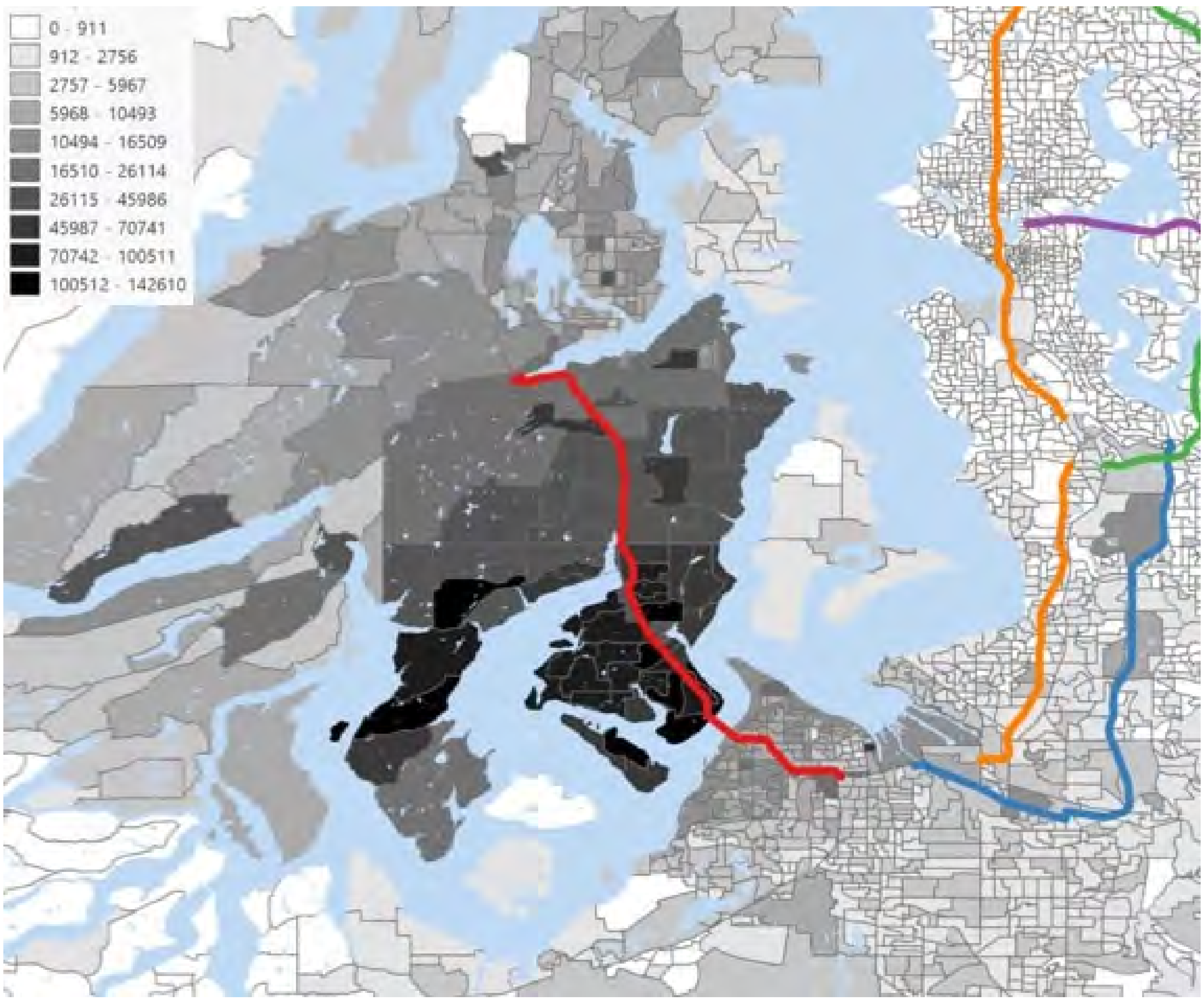


Figure 25: Trips Taken on the SR 16 Tacoma Narrows Bridge from Each CBG

This facility is slightly different from the other four toll facilities, as there is no reasonable alternative route to the Tacoma Narrows Bridge. Therefore, it makes sense that a large concentration of people travel into the city of Tacoma from west to east, but fewer households south of the bridge routinely cross the bridge.

Figure 26 (based on the Jenks methods) and Figure 27 (based on a fixed scale) show the geographic distributions of household trip making by income level for this route. SR 16 has the greatest homogeneity for the geographic origin of users by income level. That is, a substantial number of people of all household income categories use the facility, and many of the CBGs that access the bridge comprise users in all income categories. Figure 27 shows that trips made from all income levels are widely distributed throughout the Pierce County block groups north of the bridge, as well as on the Kitsap peninsula. The levels of trip making for all four income quadrants are very similar, indicating the homogeneity of facility use. This again is indicative of the fact that there is no viable alternative to the Tacoma Narrows Bridge, so people who want to make a trip between the peninsula and the mainland must pay the toll regardless of income. It also shows that there is sufficient financial incentive for many of these users to choose to pay electronically, rather than choosing to pay at the toll booth, as payments at the toll booths do not appear in WSDOT's electronic toll transaction records.

Figure 28 shows the final demographic profile, which illustrates the use of the SR 16 Tacoma Narrows Bridge. As seen with SR 99 above, the overall demographic user profile is similar to that observed in the overall regional population. However, unlike all previously presented toll facilities, the data from WSDOT's toll transaction system show that higher income households are under-represented as users of SR 16 in comparison to their proportion of the regional population. Interestingly, the LBS data suggest that these higher income households are present in excess of their share of the regional population. The project team believes that this is a function of the slight over-representation of higher-income households in the LBS data. (Higher income households are more likely to own smartphones.)

Figure 28 also shows that SR 16 has the highest fraction of toll paying customers in the middle-income range, with more than 14 percent of toll transactions associated with households with incomes of between $75,000 and $100,000 annually. SR 16 also has the highest fraction of toll payments in all income categories from $100,000 down in comparison to the other four toll facilities. This is due in part to the lack of an alternative non-toll option and in part to the presence of more low-income households on the Kitsap peninsula that need to travel to urban areas south of the bridge for activities and services not available north of the bridge.

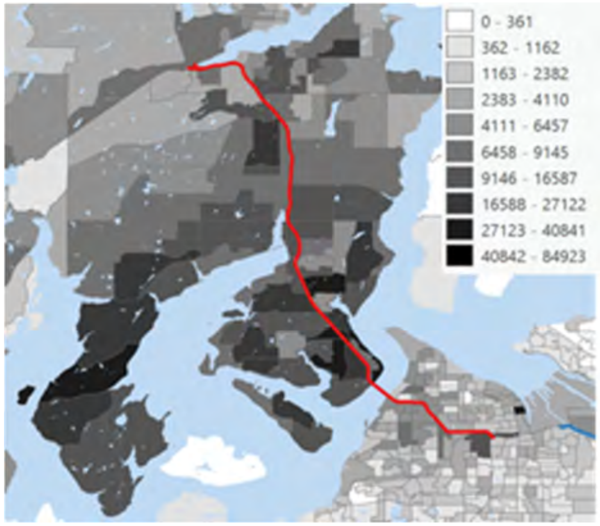
A) Number of Households with Income up to $49,999

B) Number of Households with Income from $50,000 to $99,999

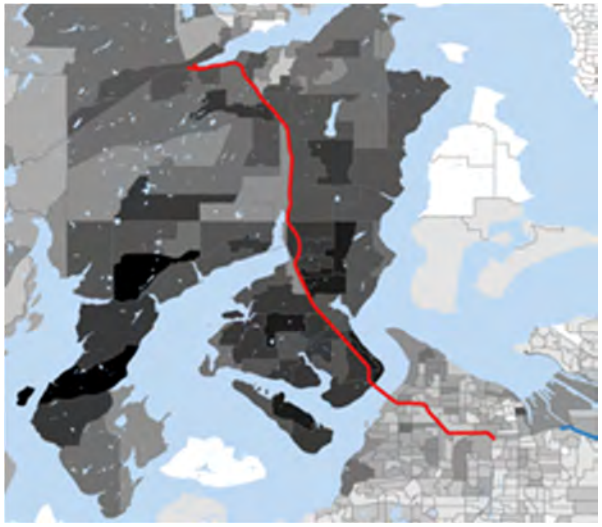
C) Number of Households with Income from $100,000 to $149,999

D) Number of Households with Income Above $150,000

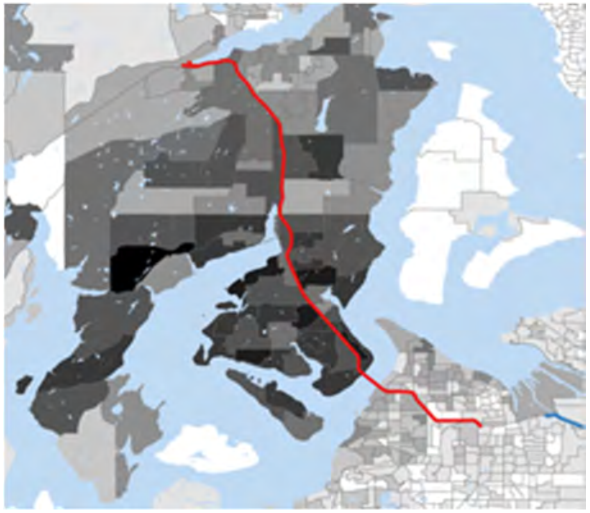
Figure 26: Income Quadrants for Trips Taken on the SR 16 Tacoma Narrows Toll Bridge from Each CBG



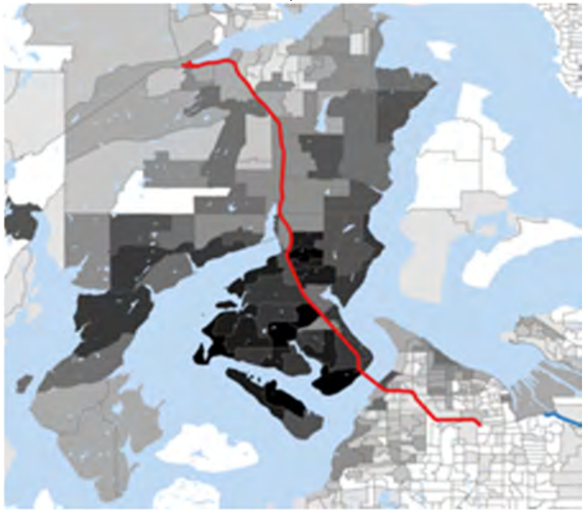
A) Number of Households with Income up to $49,999



B) Number of Households with Income from $50,000 to $99,999



C) Number of Households with Income from $100,000 to $149,999



D) Number of Households with Income Above $150,000

Figure 27: Income Quadrants for Trips Taken on the SR 16 Tacoma Narrows Toll Bridge with Fixed Income Scales

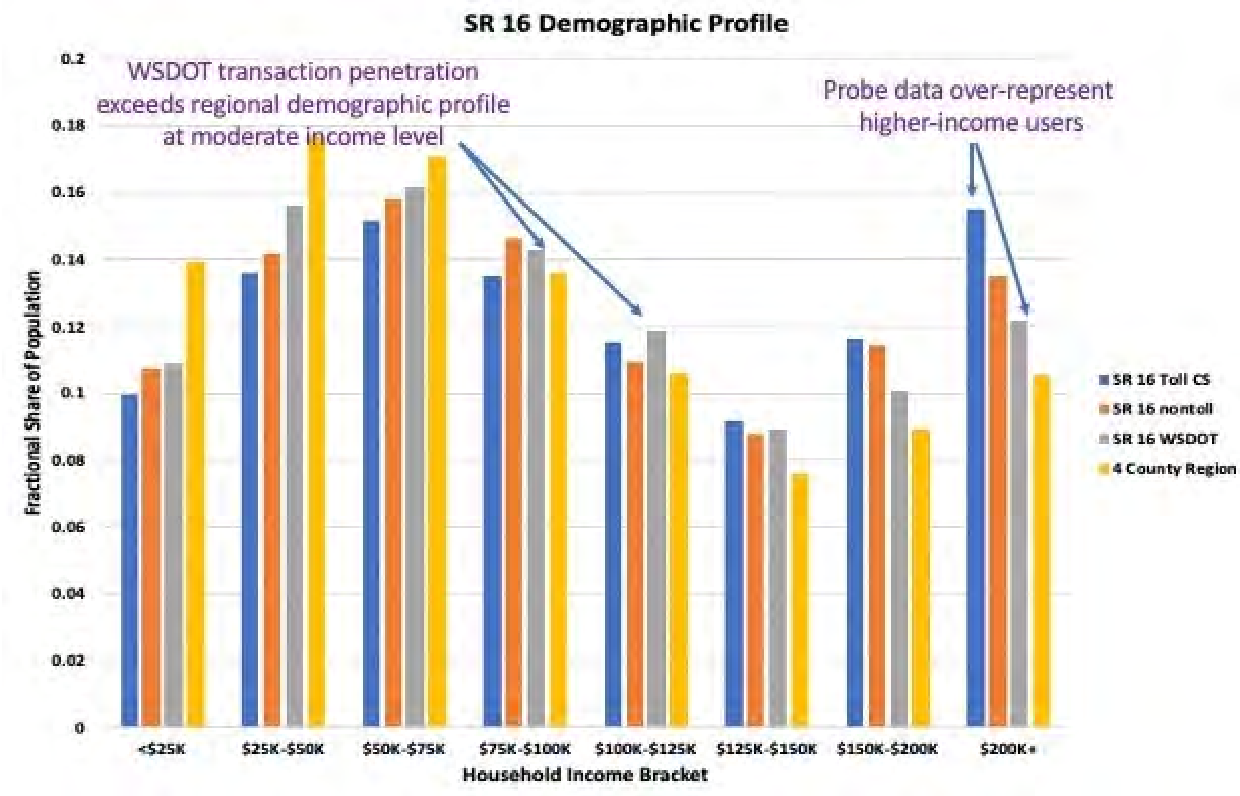


Figure 28: Income Profile for SR 16 Users

COMPARISON ACROSS TOLL FACILITIES

This section uses the results from the previous subsections to make comparisons between different toll corridors and facilities.

Who Uses WSDOT's Toll Facilities

Figure 29 summarizes the demographic profiles of trips made on all five WSDOT toll facilities. It illustrates the number of trips made on each facility by households of each of the primary census income categories. It shows both the volumes of toll trips on each facility and the relative income distributions of those trips. As noted earlier in this report, household incomes were estimated on the basis of the census block group in which bills were sent for that account, with commercial accounts (accounts with six or more vehicles) excluded from the income calculations. Figure 30 shows this same distribution but normalized against the total number of trips made on each facility; they allow comparison of the relative number of trips made on each facility by each income category.

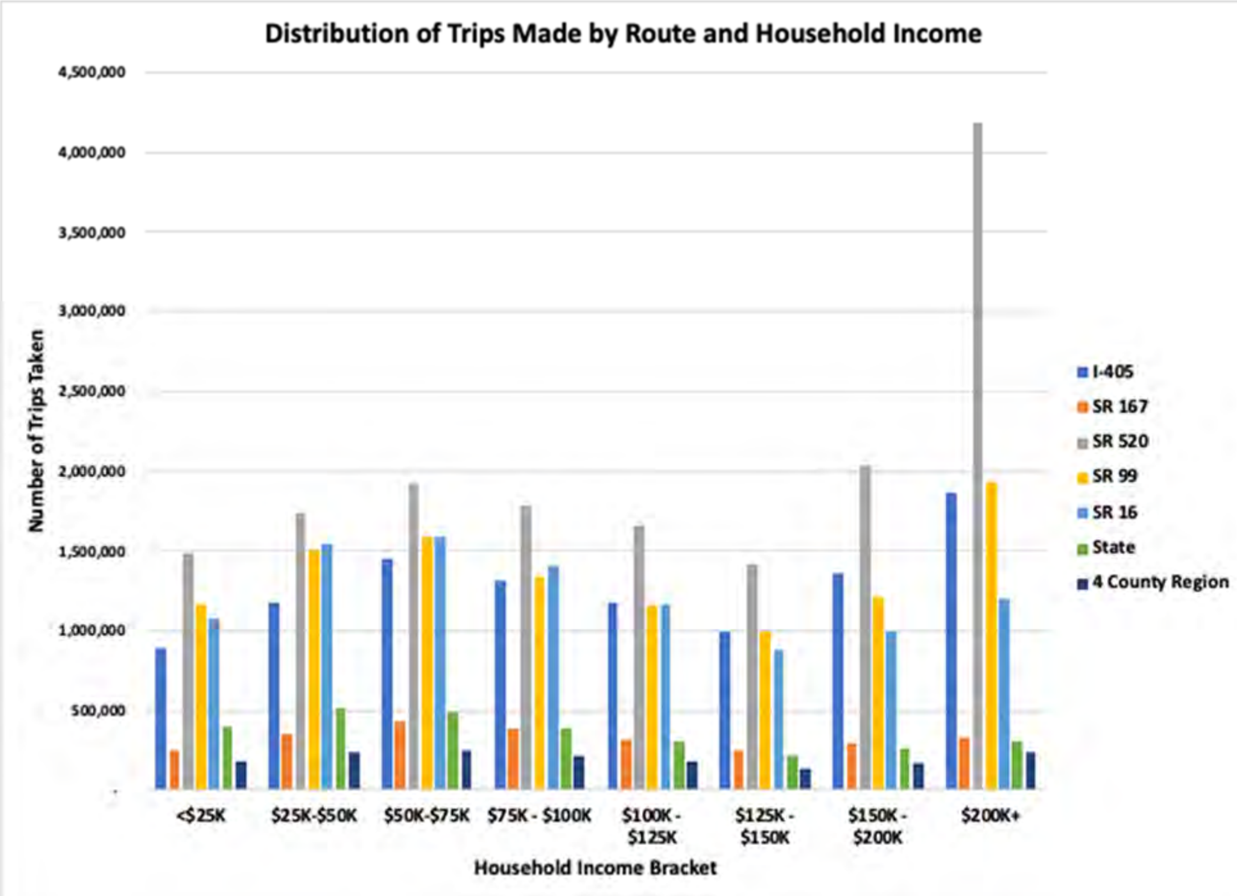


Figure 29: Number of Trips by Annual Household Income by Toll Facility

Among the key take-aways from Figure 29 are the much lower volumes of tolled trips taken on the SR 167 HOT lanes in comparison to the other four toll facilities. This is partly because this is a one-lane facility in each direction, and partly because there is little incentive to pay to use the facility during much of the day because the GP lanes next to the HOT lane are uncongested. A second major take-away is the very large number of trips taken on SR 520 by higher-income households. This is due to the combination of the very large demand for travel across Lake Washington, given the location of the lake in the heart of the Seattle/Puget Sound metropolitan region, the high capacity of the bridge (three lanes in each direction) and consequent very high use of this urban expressway, and the SR 520 bridge's location in a relatively wealthy portion of the region.

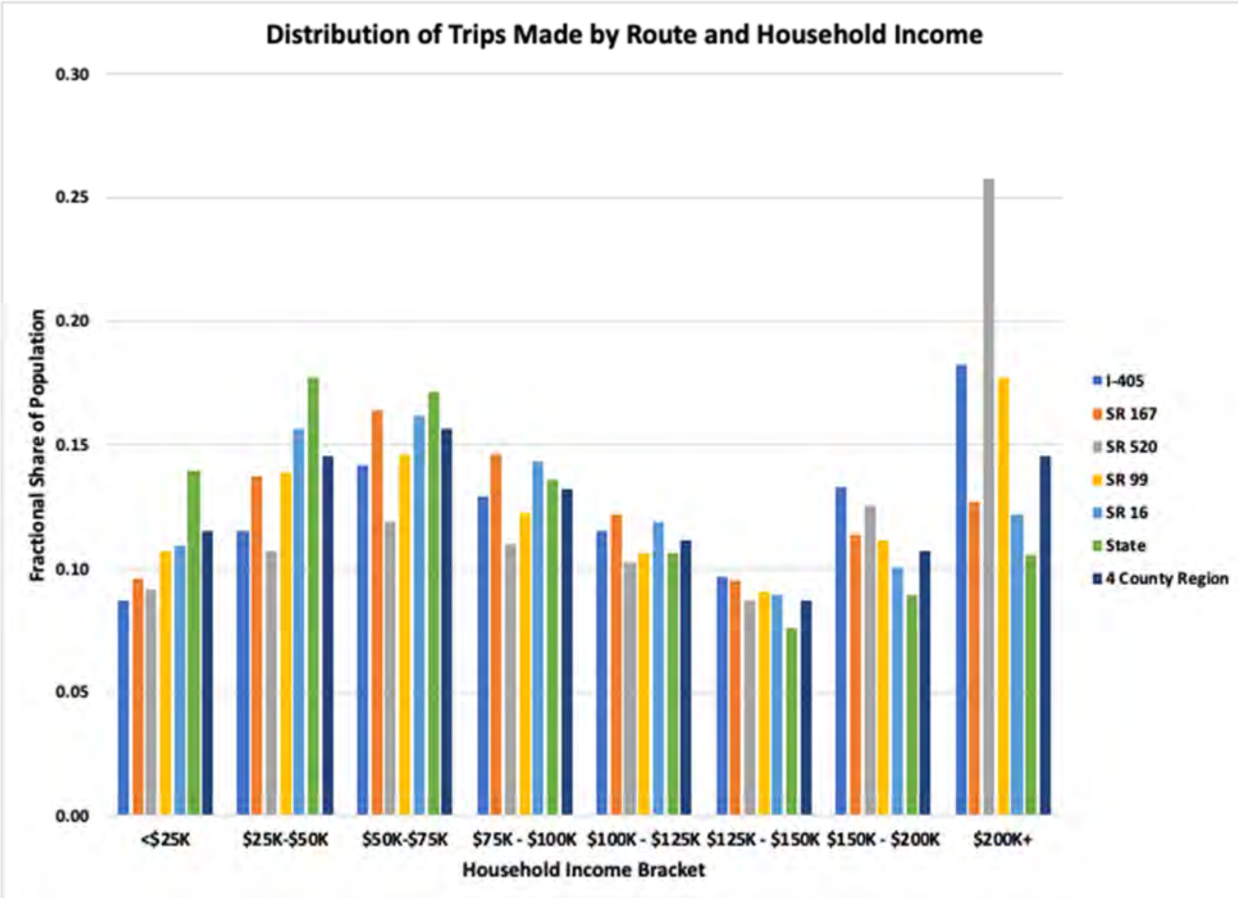


Figure 30: Normalized Distribution of Trips by Income by Toll Facility

In Figure 30, the effects of road size are removed by normalizing the Y-axis so that it shows the percentage of trip made, rather than the total number of trips. This figure provides a better understanding of the relative use of each of the toll facilities by households of different incomes, as now all trips are expressed as a fraction of trips made on that facility. Figure 30 also adds two new lines to the histogram, one for the distribution of household incomes for the entire state and one for the distributions of household incomes within the four-county Puget Sound region. These new data are taken from the

In Figure 30, the fact that the four-county region is wealthier than the rest of the state is apparent, given the relative size of the dark blue and green lines on the right side of the income distributions. It is also clear that a very large proportion of trips on SR 520 are made by the wealthiest households, and both the I-405 HOT lanes and the SR 99 tunnel are also roads on which a disproportionate number of tolled trips are made by wealthier households. As a result, a larger share of the cost of these facilities is born by wealthier households. In return, these households gain travel advantages. Also apparent in Figure 30 is that toll accounts from wealthier households are underrepresented on the SR 167 HOT lanes and the SR 16 Tacoma Narrows bridge, at least in relation to the overall four-county population. These facilities are interesting in that the middle-income categories ($60,000 to $125,000 annual household incomes) are slightly over-represented in toll payments on these roadways, whereas the wealthiest households are under-represented relative to the region's population.

Figure 31 presents how frequently vehicles with toll accounts[12] used the five facilities during the study year. This graphic shows that the majority of accounts using all five toll facilities use those facilities infrequently. Over 450,000 vehicles used the SR 99 tunnel once and only once between July 2021 and June 2022. This is 100,000 more single-use accounts than any of the other four WSDOT toll facilities. In contrast, SR 520 carries a greater number of vehicles with accounts that use that roadway frequently. This is true partly because of the high volume of use on SR 520 and partly because a large percentage of SR 520 accounts use the bridge routinely.

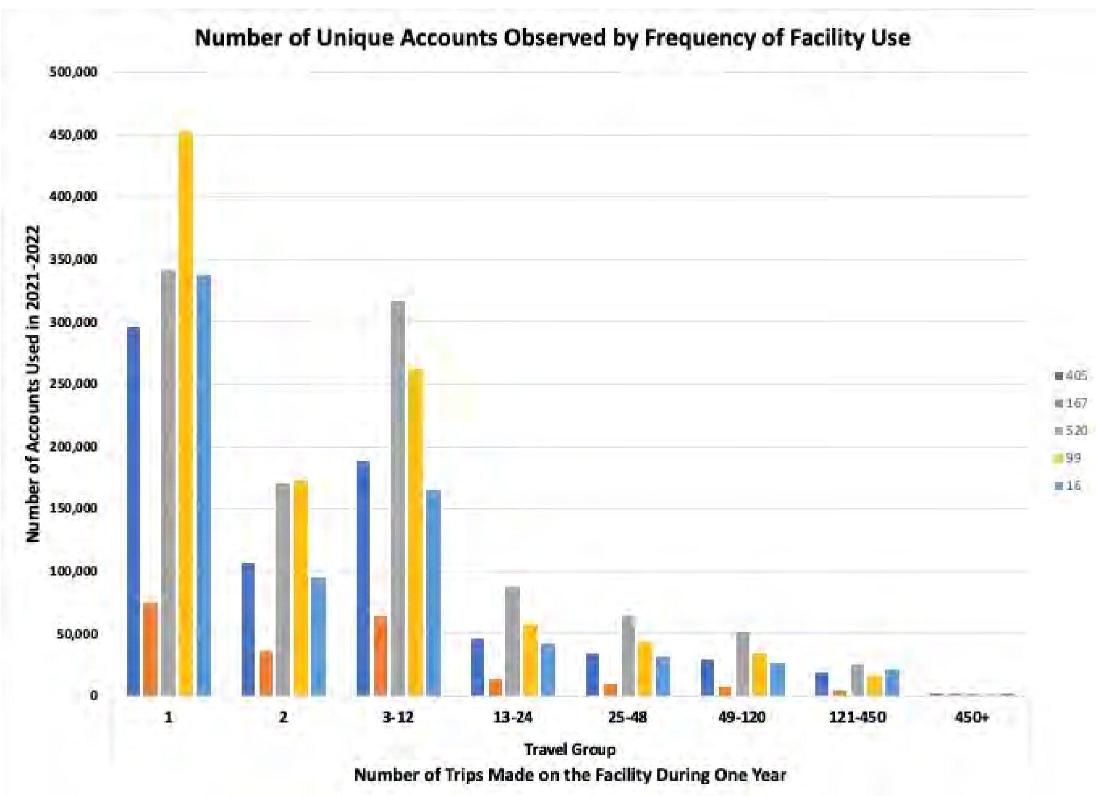


Figure 31: Number of Accounts Observed by Frequency of Facility Use

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[12] "Accounts" include toll tag and pay-by-mail accounts with WSDOT, as well as the addresses of license plates whose owners have been billed because that vehicle is not registered with Good to Go!.

Figure 32 shows this same relationship between payment accounts that use a facility infrequently and those that use it frequently, but it normalizes that relationship to the total number of users on the facility. In Figure 32 it can be seen that despite the very large number of one-time users on SR 99, SR 16 has a higher fraction of one-time customers than SR 99. This is partly due to the fact that SR 16 carries a large amount of recreational travel—and thus individuals who use the bridge infrequently—and partly due to the fact that tolls are paid in only one direction on SR 16. That is, an out-and-back trip on SR 16 results in only one transaction, but an out-and-back trip via the SR 99 tunnel results in two transactions.

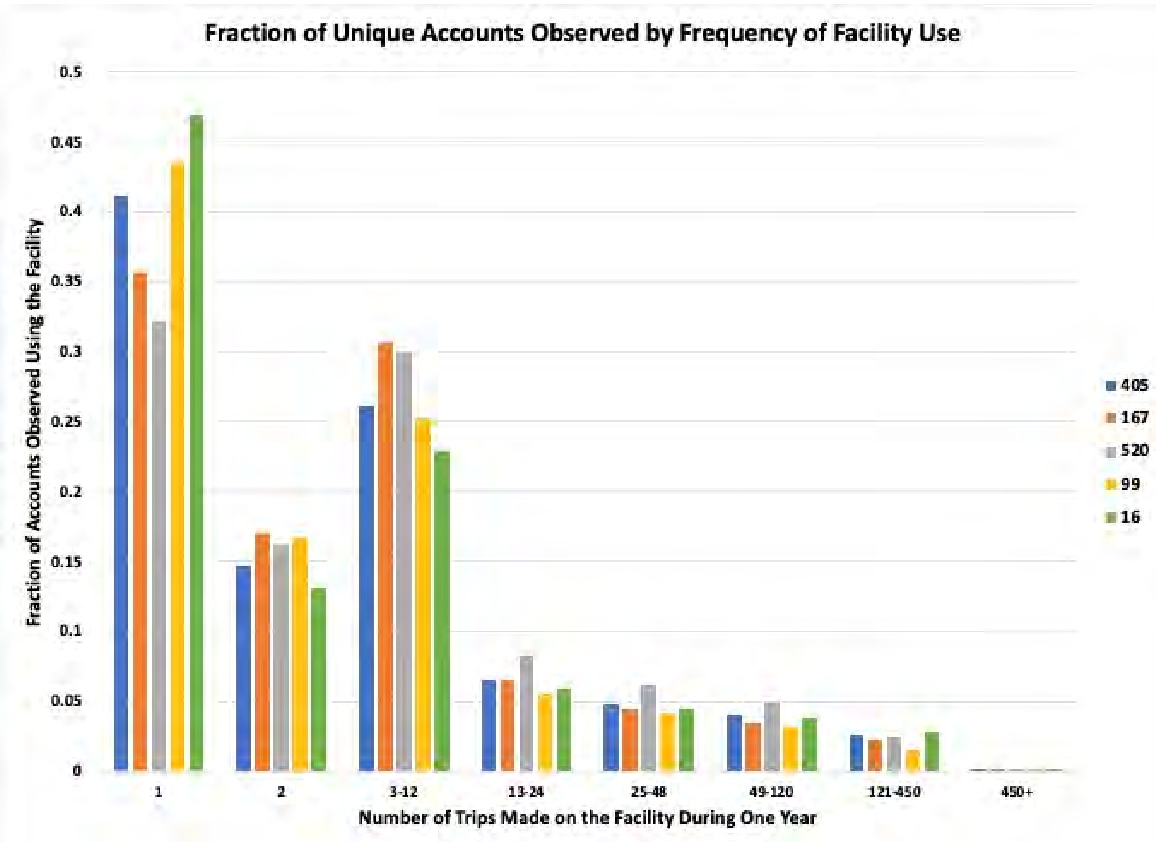


Figure 32: Fraction of Accounts by Frequency of Use by Toll Facility

Figure 32 also shows that SR 520 has a higher percentage of frequent bridges users. The graphic also shows that SR 16 is somewhat unique in that it has a high proportion of one-time users and a relatively high percentage of frequent users. Many of these frequent users are likely commuters who live on the Kitsap side of the bridge and work on the Tacoma side. Unlike SR 16, SR 520 has the lowest fraction of one-time users to go along with its above average number of high-frequency users. SR 99 is more oriented toward infrequent users, with among the smallest percentages of frequent users. Finally, SR 167 has more semi-frequent users than the other toll facilities.

CONCLUDING THOUGHTS

Overall, these graphics show that geography drives the use of toll facilities more than the tolls themselves, except that in most cases the highest household income brackets make more toll trips than a simple analysis of their share of the regional population would forecast. This is to be expected in that higher incomes lead to more discretionary travel and therefore higher trip rates. The one exception is on SR 16, where higher-income households are observed slightly less than the regional population would predict.

However, when good alternatives to paying a toll are present, as expected the share of toll paying trips increases as household income increases, especially above $75,000 annual income. Below that income bracket, travel behavior appears fairly constant. Above that bracket changes in travel behavior are more apparent.

At this income point, the effects of local geographic demographics, combined with the relative quality of alternative routes, starts to produce differences in travel behavior. For example, SR 520, where the travel shed is heavily weighted toward higher-income households, shows a very significant jump in toll payment versus toll avoidance in those higher-income brackets. These households are more likely able to pay the toll, and they are thus more willing to "purchase" travel time advantages when they occur for their specific trip origins and destinations.

SR 99 experiences a similar, but much lower, increase in trip making by higher-income households. Most trips that could use the SR 99 tunnel have far more alternative routes than trips on SR 520 and fewer origin/destination pairs for which the time savings drive additional toll trips. In addition, SR 99 appears to be a much more common dynamic or one-time route choice, on which for specific occasions, whether because of the origin/destination pair or because of specific traffic conditions on alternative routes (e.g., I-5), singleton trips are made.

The one exception to this finding is SR 167, where the Cambridge Systematics LBS data showed that higher-income households use the combined SR 167 GP and HOT lanes at slightly higher rates than the regional income profile would suggest. However, those higher-income households pay to use the HOT lanes slightly less frequently than the regional population distribution would suggest. On SR 167, HOT lane use by those in the moderate-income brackets ($60,000 to $125,000 annually) slightly exceeds their total use of the facility as a fraction of trips.

The large number of single-use trips observed on SR 99 is also observed on SR 16, but for what are likely different reasons. SR 16 is assumed to serve a large number of recreational trips for which there are no rational, toll free alternatives. Therefore, the large fraction of single-use SR 16 trips is believed to originate from those periodic recreational trips. In contrast, the reasoning behind the singleton use of SR 99 is assumed to be more spontaneous routing decisions as the result of congestion on parallel routes.

Chapter 3. Value of Time and Value of Reliability

In 2019 the UW's Data Science for Social Good (DSSG) program conducted an analysis for WSDOT's Toll Division that examined the equity of the I-405 Express Toll Lanes (Leung et al. 2019). That study used data for all of 2018, and it computed the value of time (VOT) and value of reliability (VOR) observed in traveler behavior to describe when people decided to pay for Express Toll Lane trips and when they decided to not pay for those trips but remained in the GP lanes. The work was based on a 2018 paper by Daniel Brent and Austin Gross.

This chapter discusses the changes observed in VOT and VOR when the analysis results from 2021 to 2022 were compared to the original 2018 results. This report then describes the application of the same technique used in the DSSG project to SR 167.

METHODOLOGY

The following methodology discussion is taken from the DSSG report, "I-405 Express Toll Lanes: Usage, Benefits, and Equity" (Leung et al. 2019), as the technique we used was taken from that study.

The model developed to estimate VOT, VOR, and price elasticity measured the number of users who entered the HOT lane in 2-minute increments between July 1, 2021, and June 30, 2022, for each possible trip. Here "trip" was defined as the origin being the entry point to the HOT lane and the destination being the exit point from the HOT lane. For SR 167, the entry and exit points were defined as the first and last toll gantries at which the vehicle was identified. The model was based on that developed by Daniel Brent and Austin Gross in their paper, "Dynamic Road Pricing and the Value of Time and Reliability" (Brent and Gross 2018).

To quantify the situation a driver faces when deciding to enter the toll lane, this approach uses the length of the trip in miles and the estimated time savings, estimated reliability, toll, speed, and volume of the general purpose lanes to predict the number of drivers entering the facility at a given time and at a specific entry point. From this model, it is possible to calculate the average value of time, value of reliability, and price elasticity for the corridor. This is done using a linear regression model to describe the relationship between the variables of interest. The estimating equation is:

$$y_{ijt} = \beta\, Toll_{ijt} + \Omega\, GPspeed_{it} + \eta\, Gpvolume_{it} + \varphi\, EstTimeSaving_{ijt} + \lambda\, Reliability_{ijt} + \theta\, TripLength_{ij} + u_{it}$$

where y_{ijt} is the count of SOVs that enter at time t and gate i and are heading to gate j, and u_{ijt} is the error term. To obtain estimates for VOT and VOR, we calculate $-(\varphi / \beta)$ and $-(\lambda / \beta)$ to find the rate of substitution between time/reliability and money, as described in the modeling section.

Price elasticity can then be calculated by using the ratio of the average value of toll and average volume multiplied by β and can also be calculated by using averages at different subsets of data (e.g., northbound versus southbound and peak versus off-peak).

Value of Time

VOT is difficult to measure because of the differences between achieved travel time savings (how much time people actually save by traveling in a HOT lane) and estimated travel time savings (how much time users thinks they will save when deciding to use the HOT lane).

To help overcome this problem, estimated time savings are modeled as a function of the visual cues available to potential users at the point in time and space where they make the decision to enter the HOT lanes—the current toll, the time of day, the route, the speed, and volume of the general purpose lanes at that location, and the speed and volume of the HOT lane. The toll is added because this may be a determining factor in whether a person chooses to use the facility. If the toll is high, it may signal to the user that worse traffic is in the general purpose lanes ahead. For I-405, direct access ramp entries were excluded from the model because drivers there have very limited access to local traffic information. Figure 33 shows the relationship between actual and estimated time savings.

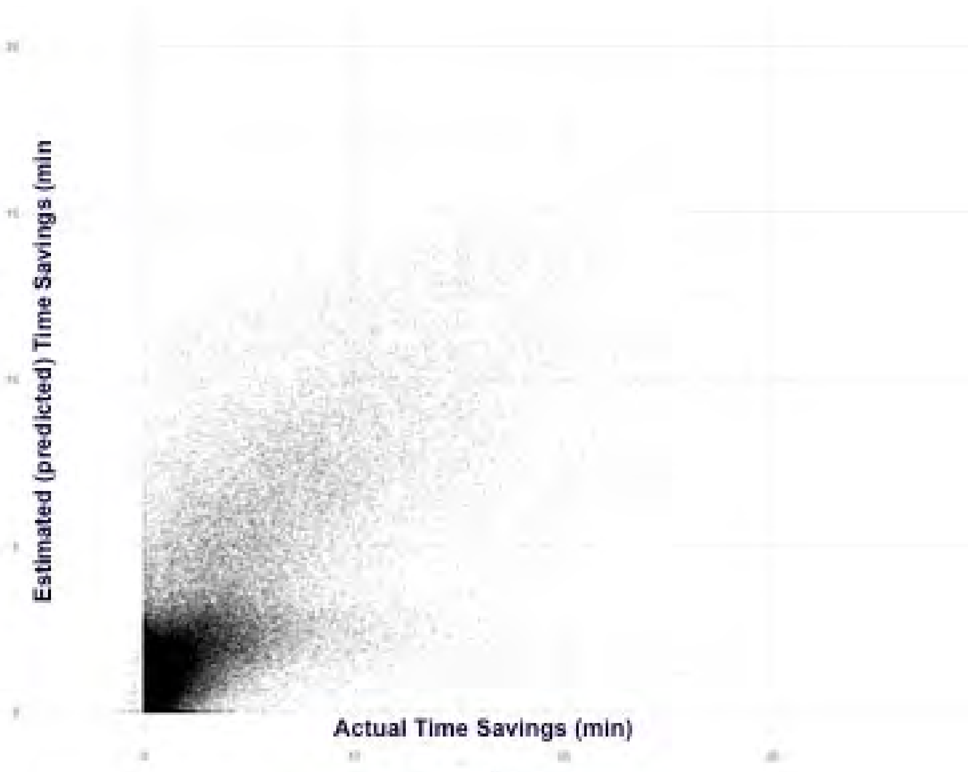


Figure 33: Actual versus Estimated (current conditions-based prediction) Time Savings

A simple VOT can be obtained by dividing the toll by the achieved travel time savings, but previous studies have demonstrated that this can overinflate the effect to amounts greater than $100 per hour. To obtain a more precise estimate, the model's estimated effect of time savings was selected and divided by the negative effect of price.[13] This yielded a VOT based on estimated time savings at a much more reasonable rate.

Value of Reliability

Reliability determines how well the facility functions for a user. To visualize this effect, it is useful to imagine a commuter who knows that the commute takes a certain amount of time each day and also knows that the commute time can vary depending on different traffic conditions such as weather. This variability in commute times was quantified by taking the difference between the 80th and 50th percentile travel times for both the HOT and general purpose lanes by time of day.

[13] This represents the marginal rate of substitution between time and money. Brent and Gross (2018) also described this as an estimate of the marginal utility of buying into the toll ("negative one times the dis-utility of the toll"), also defined as the marginal utility of income lost.

The difference between these values for each lane provided reliability estimates.[14] The more reliable a commute is, the less variability there will be in travel time.

Figure 34 shows average time savings and reliability estimates in 15-minute increments for full-corridor trips in each direction on I-405. Generally, time savings and reliability correlate well, but during certain sections of peak hours, reliability drops. This reflects periodic congestion due to high demand for the facility in the section of the I-405 Express Toll Lanes that approaches Bothell during portions of the AM peak period.

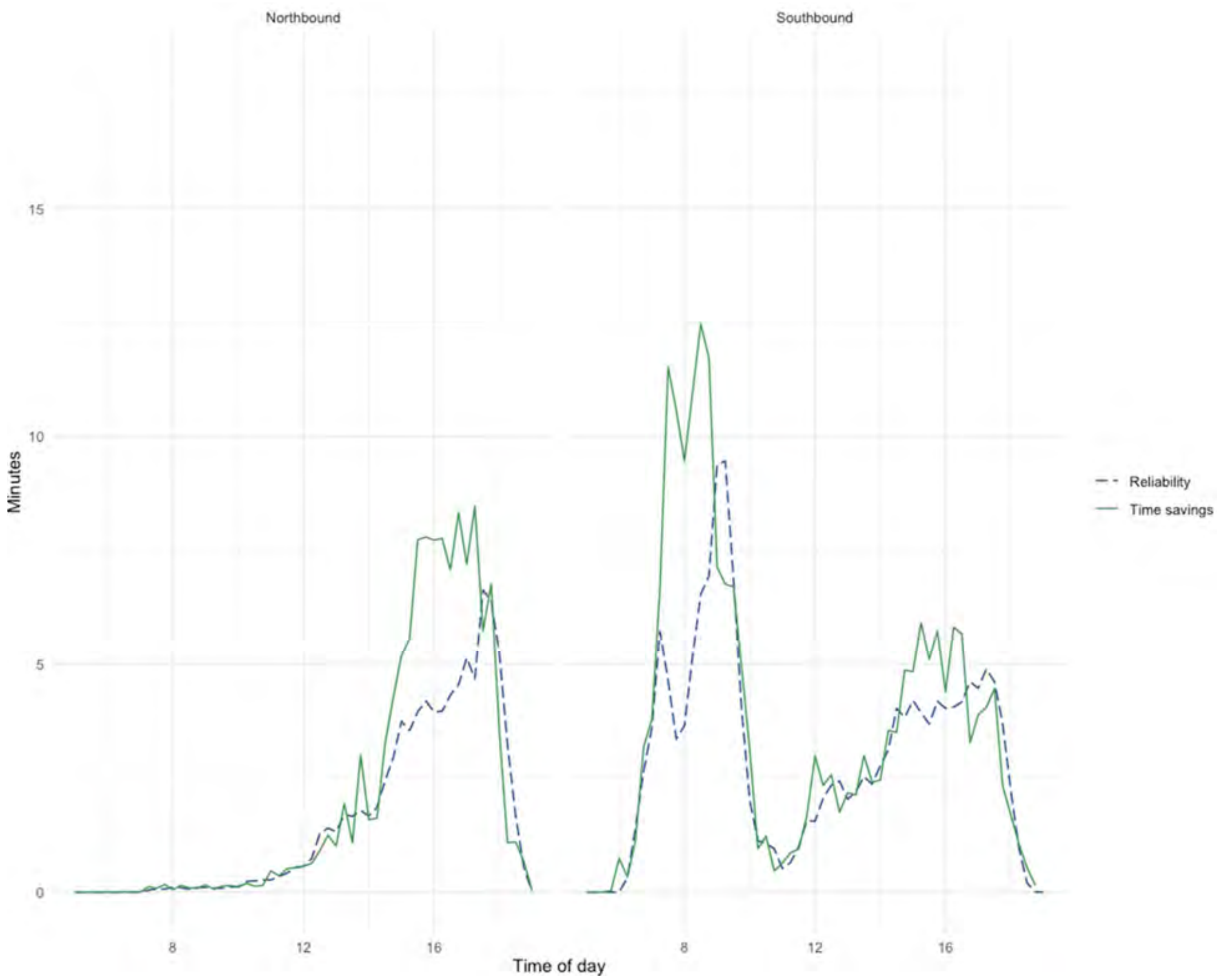


Figure 34: Time Savings and Reliability Estimates in 15-Minute Increments for Full-Corridor Trips in Each Direction

[14] This is also known as the mean-variance model, from Small, et al. (2005).

Price Elasticity

Price elasticity of demand describes changes in user behavior when users are faced with a change in price. Negative values represent economic goods that follow a normal demand curve: an increase in price decreases demand. Previous studies of toll lanes have estimated positive price elasticity, meaning the opposite: demand increases as price increases. Brent and Gross attributed this finding to studies neglecting to control for the correlation of increases in toll and volume. That is, people likely do not opt to use the toll lane solely because the price is higher but rather because both volume and price increase as a result of increased traffic demand, and therefore the HOT lane becomes a more desirable good. An alternative theory about why demand would increase as price increases is that drivers view higher prices as a signal of worse traffic in the downstream GP lanes and therefore choose to enter the HOT lanes before prices escalate further.

I-405 VOT/VOR FINDINGS

Introduction to the I-405 Express Toll Lanes

The I-405 Express Toll Lanes (ETLs) are high occupancy vehicle toll (HOT) lanes on the northern half of I-405, stretching from downtown Bellevue to the northern freeway interchange of I-405 with I-5 in Lynnwood. Figure 35 is a map of the ETLs. The southern-most portions of the ETLs are two lanes wide beside three general purpose (GP) lanes. The northern third of the corridor has one ETL lane and two or three GP lanes, depending on the specific location. The northbound lane drops from a 3+2 to a 2+1 configuration as northbound traffic approaches the exits to SR 522. WSDOT has added a third GP lane as part of the entrance from SR 522 to northbound I-405 to reduce congestion caused by the lane drop, given the large traffic volumes continuing north on I-405.

Entrances to and exits from the ETL lanes are limited. This limits the geographic locations where entrance/exit decisions can be made in rea -time. There are ten of these entrance/exit locations northbound and eleven southbound. Toll gantries exist at each of these locations. Toll tag or license plate reads at each of these locations allow the toll system to determine the ETL "trip," defined by the entrance/exit points, made by each vehicle.

Toll rates on the ETL are set dynamically, based on the traffic conditions in both the GP and HOT lanes. Prices rise to decrease demand for the ETLs to help prevent breakdown of the ETLs.

Figure 35: Map of the I-405 Express Toll Lanes

Toll rates are also determined by the distances traveled in the ETLs. For example, motorists entering the southern end of the facility are provided with three prices, one for each of three destinations on the facility. The price they pay, if they choose to use the ETLs, is set at the time they enter and is based on where they exit. If they exit at or before the first destination, they pay the price shown for that destination. If they exit after that destination but before or at the next exit shown on the toll pricing sign, they pay that second price, and so forth. If motorists bypass the first ETL entrance, they must use the GP lanes for several miles before they have another option to enter the ETL. Prices may change between the first entry location and the second location depending on changing roadway conditions. If motorists choose to enter at the second entry point, the rates shown at that point and at that time govern the price they pay.

<u>Performance of the Express Toll and GP Lanes on I-405</u>

Figure 36 through Figure 39 are intended to help visualize the roadway performance on I-405, which in turn influences driver behavior. Figure 36 and Figure 37 illustrate average northbound roadway performance. Figure 36 shows where weekday congestion usually forms in the GP lanes and ETLs, while Figure 37 shows where and how often stop-and-go congestion forms in the both the GP lanes and ETLs. Both figures show performance for all weekdays in 2018 and all weekdays in the period of July 2021 to June 2022.

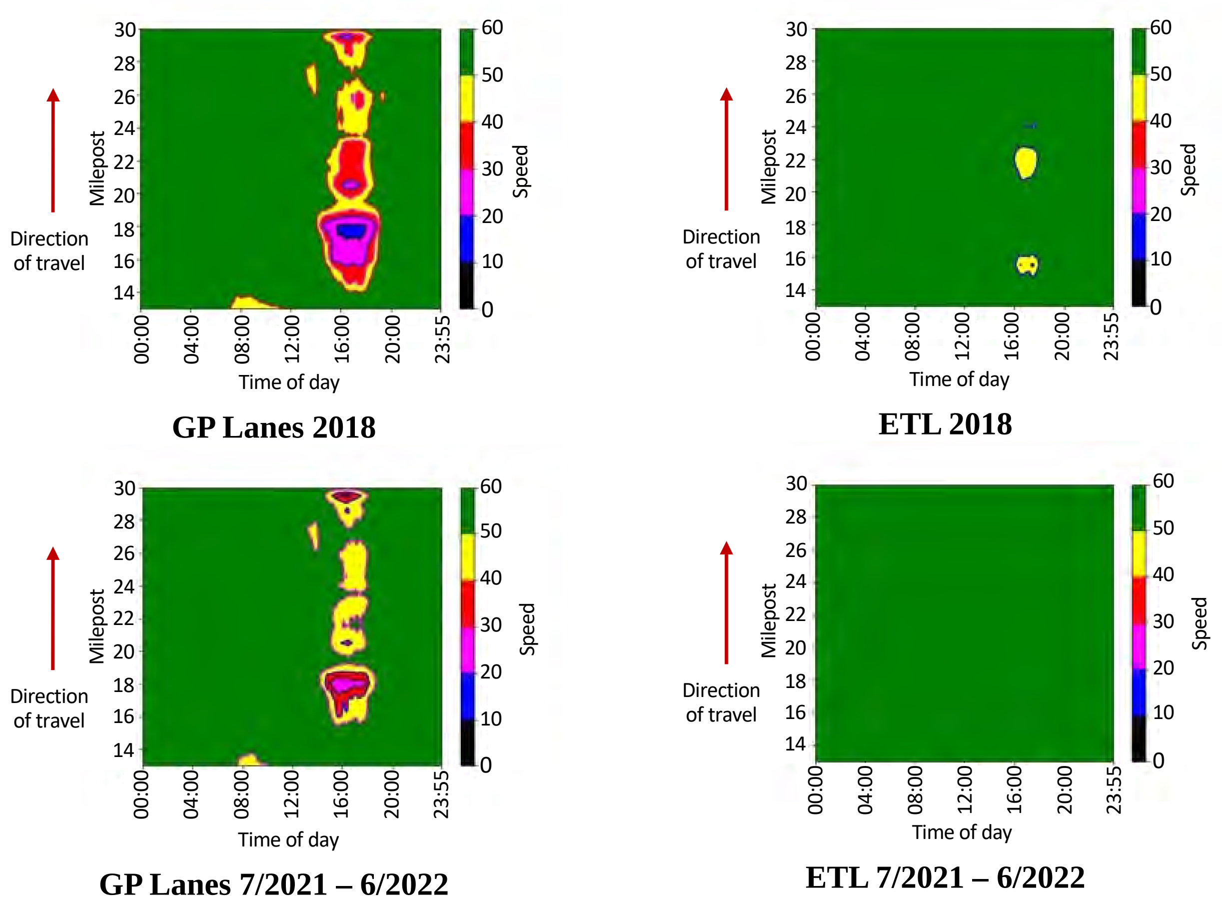


Figure 36: Northbound Mean Speed by Location and Year on I-405

These figures allow a comparison of the conditions that drivers experience in the corridor from before the pandemic to the current post-pandemic period, when travel has rebounded to a moderate degree. Other than during unusual incident conditions, northbound I-405 north of downtown Bellevue is congested only in the afternoon peak period. However, afternoon congestion can be significant. Figure 36 shows that in 2018 there was significant GP lane congestion (yellow, red, pink, and blue colors) during the evening peak period along the length of the corridor, with the most significant congestion occurring between mileposts 14 and 18, between 19.5 and 23, and beyond mile marker 28. A similar pattern is observed for the July 2021 to June 2022 period, except that the magnitude of the congestion was considerably smaller. In contrast, in 2018 there was only minimal routine slowing on the ETLs, and that congestion disappeared completely from 2021 to 2022.

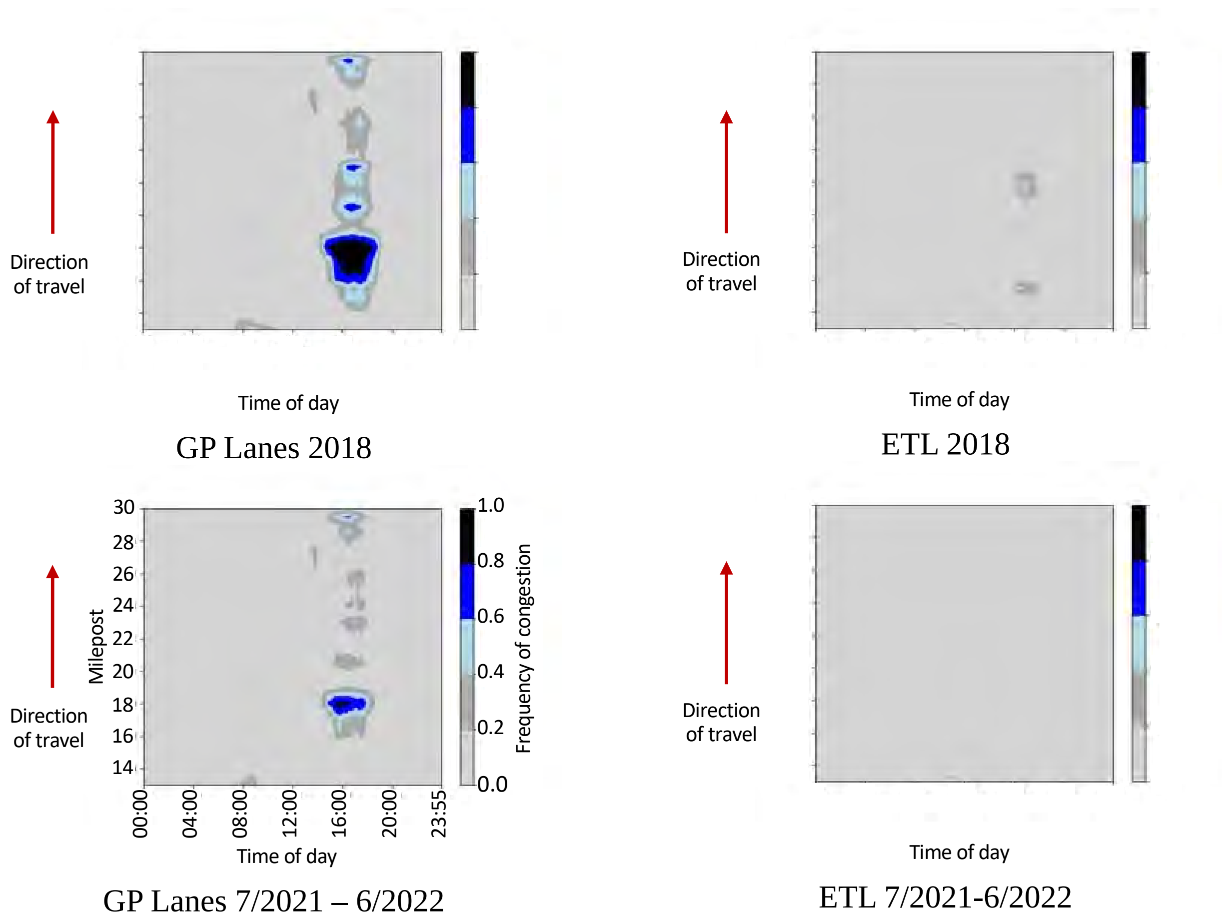
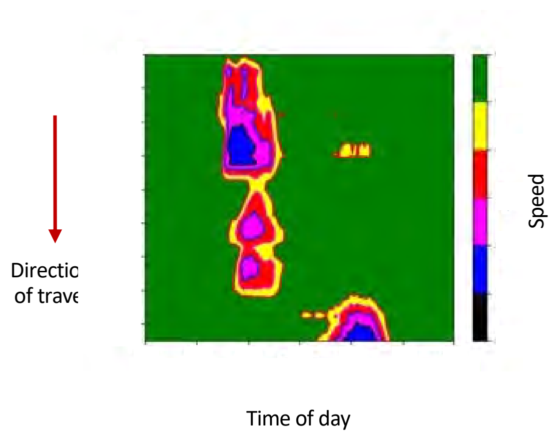


Figure 37: Northbound Frequency of Congestion by Location and Year on I-405

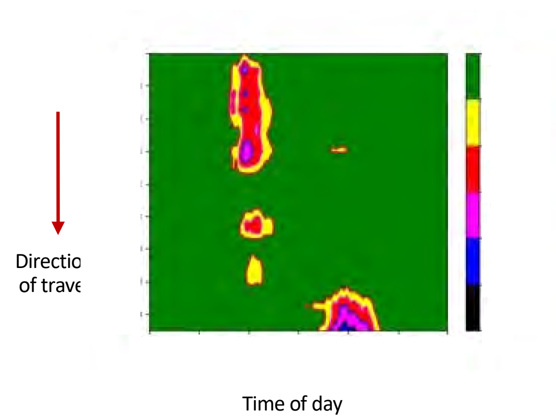
If performance is examined in terms of the frequency with which stop-and-go conditions form, the same patterns are apparent. Figure 37 shows that in 2018 the longer northbound trips in the GP lanes routinely experienced stop-and-go conditions throughout large portions of the corridor in the afternoon peak period. The segment between mileposts 16 and 19 (climbing the hill to the Kirkland/Redmond exits) experienced congestion three to five days a week, with pockets of stop-and-go congestion occurring several more times as trips continued farther north. In 2021 to 2022, while stop-and-go conditions still occurred in the GP lanes, the magnitude of that congestion was much smaller than in 2018 spatially, temporally, and in terms of the frequency of occurrence.

For the ETLs, the frequency of congestion plots shown in Figure 37, like the mean speed graphics shown in Figure 36, show that stop-and-go congestion essentially disappeared in 2021 and 2022. Congestion in the ETLs then occurred only on random days because of unusual events.

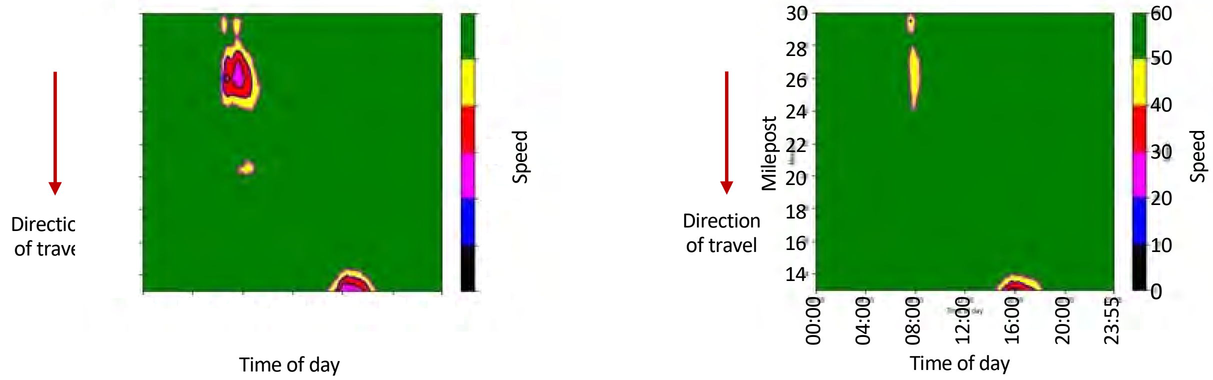
Figure 38 and Figure 39 show these same graphics for the southbound direction of I-405. Southbound traffic conditions were considerably different than those of the northbound direction. While the northbound direction of I-405 experienced congestion mostly in the evening peak hours, morning peak period congestion on I-405 was mostly in the southbound direction. (There was a routine southbound backup in downtown Bellevue during the evening peak period, which congested both the GP and HOT lanes in the ETL corridor, as well as minor southbound slowdowns in northern Bothell in the afternoon peak.) Figure 38 illustrates that routine southbound conditions in the GP lanes during morning peak hours improved in 2021 and 2022 in comparison to 2018, although considerable congestion remained, especially in the GP lanes north of the SR 522 interchange. Similar improvements are shown in the ETLs as well, where most severe congestion outside of the downtown Bellevue backups disappeared, and only minor slowing north of SR 522 remained.



GP Lanes 2018



GP Lanes 7/2021 – 6/2022

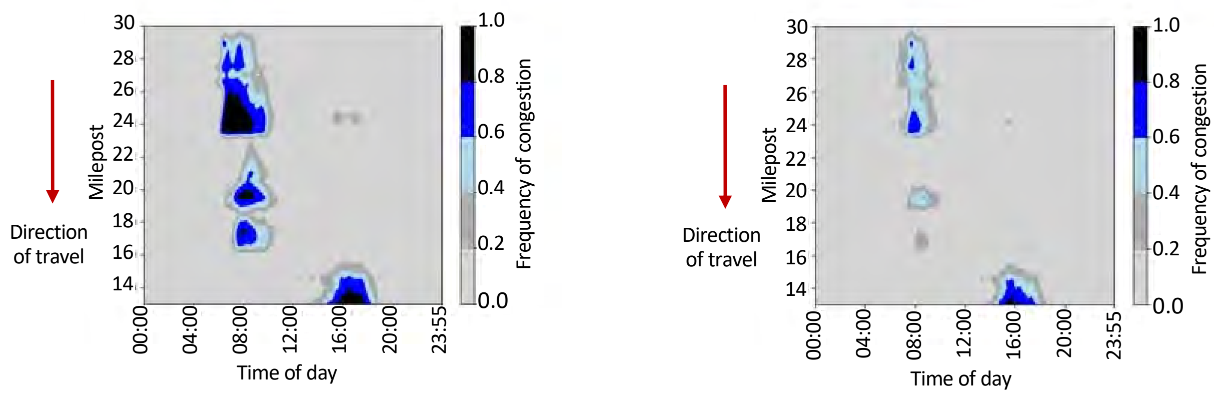


ETL 2018 ETL 7/2021-6/2022

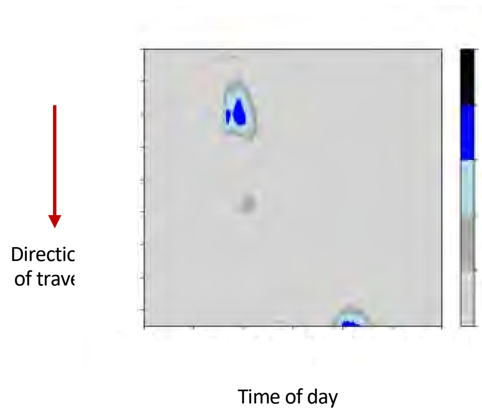
Figure 38: Southbound Mean Speed by Location and Year on I-405

The frequency of stop-and-go traffic shown in Figure 39 confirms the improvements shown in Figure 38. As a result, the ETLs became even more reliable than they were in 2018, as the congestion that pushed drivers to pay for the ETL grew smaller, and the likelihood of drivers encountering major stop-and-go congestion in the GP lanes declined.

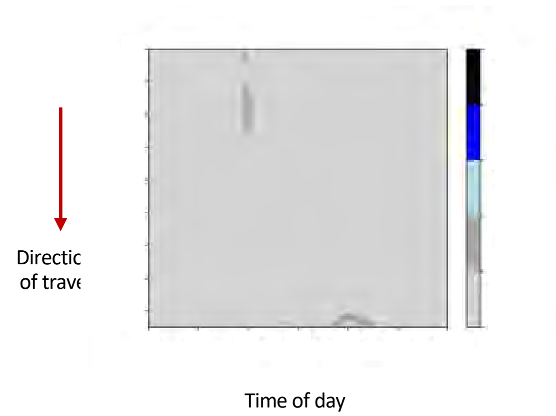
These changes can be important to drivers in relation to their willingness to pay for travel time benefits. Overall changes in travel time and reliability are summarized in Figure 40, with travel time savings computed as the mean time savings for corridor-length trips when the ETL is used instead of the GP lanes, and reliability computed as the difference between the 80th and 50th percentile travel times.



GP Lanes 2018 GP Lanes 7/2021 – 6/2022

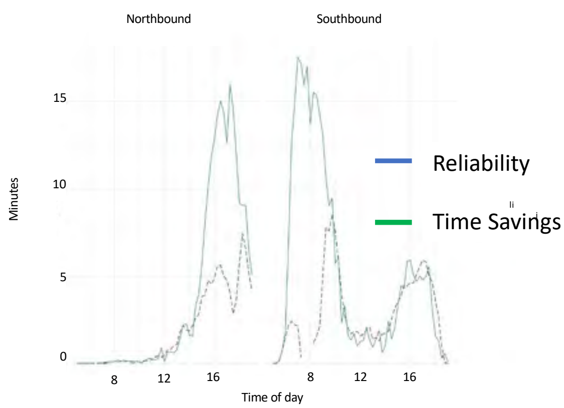


ETL 2018

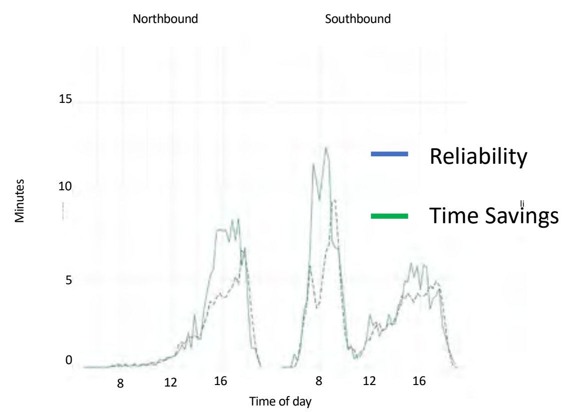


ETL 7/2021-6/2022

Figure 39: Southbound Frequency of Congestion by Location and Year on I-405



2018



7/2021 – 6/2022

Figure 40: Summary Travel Time and Reliability Savings in 2018 and 2021-2022

<u>Computed Value of VOT, VOR, and Price Elasticity</u>

Table presents the estimated VOT, VOR, and price elasticity for 2021 and 2022. These estimates are compared to the results from the 2018 analysis in the next subsection of this report. Estimates for 2021 and 2022 are provided for three specific movements, as well as a summary set of statistics for the facility. The three specific movements are defined as the two primary commuter movements, when demand for the ETLs is the highest—1) southbound in the morning peak ("AM peak") and 2) northbound in the afternoon peak ("PM peak")—as well as 3) all off-peak movements combined (Off-peak). These different movements are presented to describe the behavior of travelers making different movements under different conditions.

Table 5: Computed VOT, VOR, and Price Elasticity

Time Period	Value of Time (VOT)	Value of Reliability (VOR)	Price Elasticity
Overall – All times of day and both directions	$56.6 / hr	$14.0 / hr	-0.71
AM Peak Southbound	$56.4 / hr	$9.10 / hr	-0.83
PM Peak Northbound	$49.4 / hr	$10.2 / hr	-1.11
Off-Peak	$53.7 / hr	$15.0 / hr	-0.52

Table shows that in 2021 and 2022 the value of time in the AM southbound peak direction movements was slightly higher than that in the afternoon peak movement northbound. In all cases, the value of the reliability was much lower than the value of time. An example of how to interpret the price elasticity results is that the value of -0.83 for the AM southbound peak means that for every 10 percent increase in price, a decrease in demand for the ETL of 8.3 percent would occur.

The off-peak elasticity was lower than the peak period elasticities. This was likely due to the higher percentage of higher-income users in the off-peak. This is because they are less sensitive to price than the average user because the toll represents a smaller proportion of their disposable income. Additionally, the toll is generally lower during off-peak hours, and at lower tolls, users are less likely to be sensitive to price.

All of these are the <u>values expressed by people making the decision to use the ETL facility</u>. They are not representative of the Puget Sound region as a whole. That is, individuals who choose to stay in the GP lanes have a lower value of time than individuals who choose to pay for an ETL trip. This helps explains the very high value of time ($87.4 / hr) observed for the reverse commute. As noted in previously, there was little congestion for most of the reverse commute trips. As a result, even though the cost was low to access the ETL, the time savings obtained were small, and the value of time was very high.

In reality, drivers likely choose the ETL for reasons other than avoiding the small delays that occur in the GP lanes. One reason may be that drivers wish to use one of the direct access ramps (e.g., the ramp at Totem Lake, which provides faster access to the Evergreen Hospital Medical Complex than the GP lane exit), saving time that is not apparent in the direct comparison of ETL/HOT lane travel times and GP lane travel times. Drivers may also feel safer in the under-utilized ETLs during off-peak movements because traffic density is lower. Without survey data to describe the actual reasons behind drivers' decisions, the model assumed that these decisions were primarily based on price sensitivity, resulting in a high off-peak value of time.

Comparison of 2021 and 2022 VOT and VOR with 2018 VOT and VOR

While the new estimates of VOT and VOR for I-405 are interesting, just as important is how the changes in travel behavior caused in large part by the pandemic changed those values over time. Table compares the estimated overall VOT, VOR, and price elasticity for 2021 to 2022 with the same statistics computed in the DSSG study for 2018.

Table 6 Comparison of 2018 and 202 to 2022 VOT, VOR, and Price Elasticity

Parameter	2018	July 2021-June 2022
Value of Time (VOT)	$53.1 / hour	$56.6 / hour
Value of Reliability (VOR)	$26.4 / hour	$14.0 / hour
Elasticity	-0.64	-0.71

In comparison to 2018, the value of time increased in 2021 to 2022 by about $3.50/hour. Meanwhile, the aggregated VOR in 2021 to 2022 decreased by $12.40/hour in comparison to that in 2018. This combination means that post-pandemic drivers valued current conditions slightly more and were less sensitive to the historical performance of the GP and ETL roadways. At the same time, price elasticity in 2021 to 2022 estimated to be slightly higher. That is, post-pandemic, a 10 percent increase in toll would, on average, decrease ETL demand by 7.1 percent. This is a 0.7 percent higher rate than that observed in 2018.

These overall changes apply to the three major time periods, although the degree of change varied from one period to another. Figure 41 shows how value of time changed from 2018 to 2021-2022 for AM peak southbound, PM peak northbound, and off-peak. In all three cases, the value of time of ETL users increased slightly in 2021-2022. The changes in the two peak period movements were similar in size, whereas the change observed in the off-peak movement was very small (and not statistically significant).

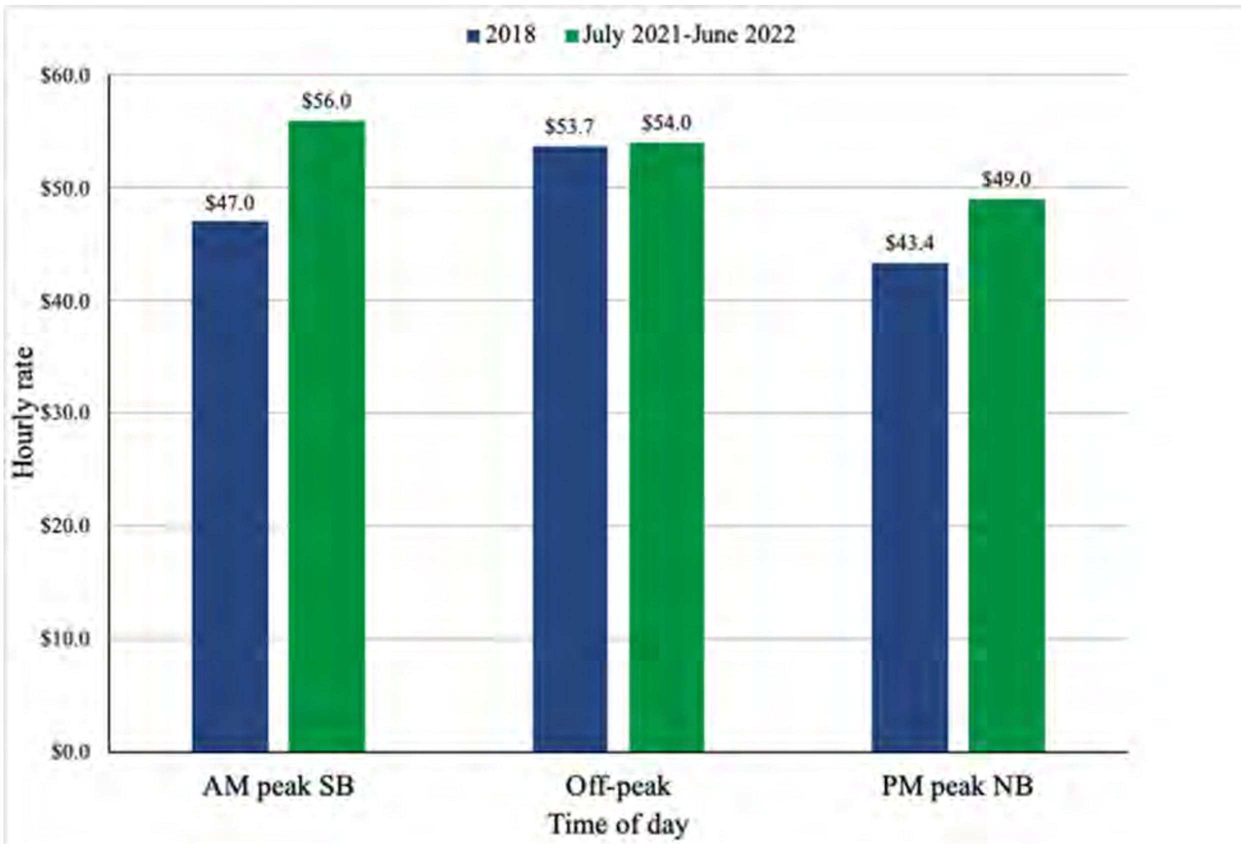


Figure 41: Comparison of Value of Time on I-405 ETL 2018 vs 2021-2022

Figure 42 shows that the value placed on travel time reliability declined for all of the primary movements between 2018 and 2021-2022. Unlike the changes in the value of time, which were relatively small, the changes in the value of reliability were much greater. Even in the PM peak, when 2018 data revealed a fairly low value of reliability of around $19, the 2021-2022 data showed basically half of that value. The drop in the value of reliability in the AM peak and off-peak movements were much more significant, with the new AM peak value being roughly 20 percent of the earlier value. These results contrast somewhat with the change in overall price elasticity, which increased.

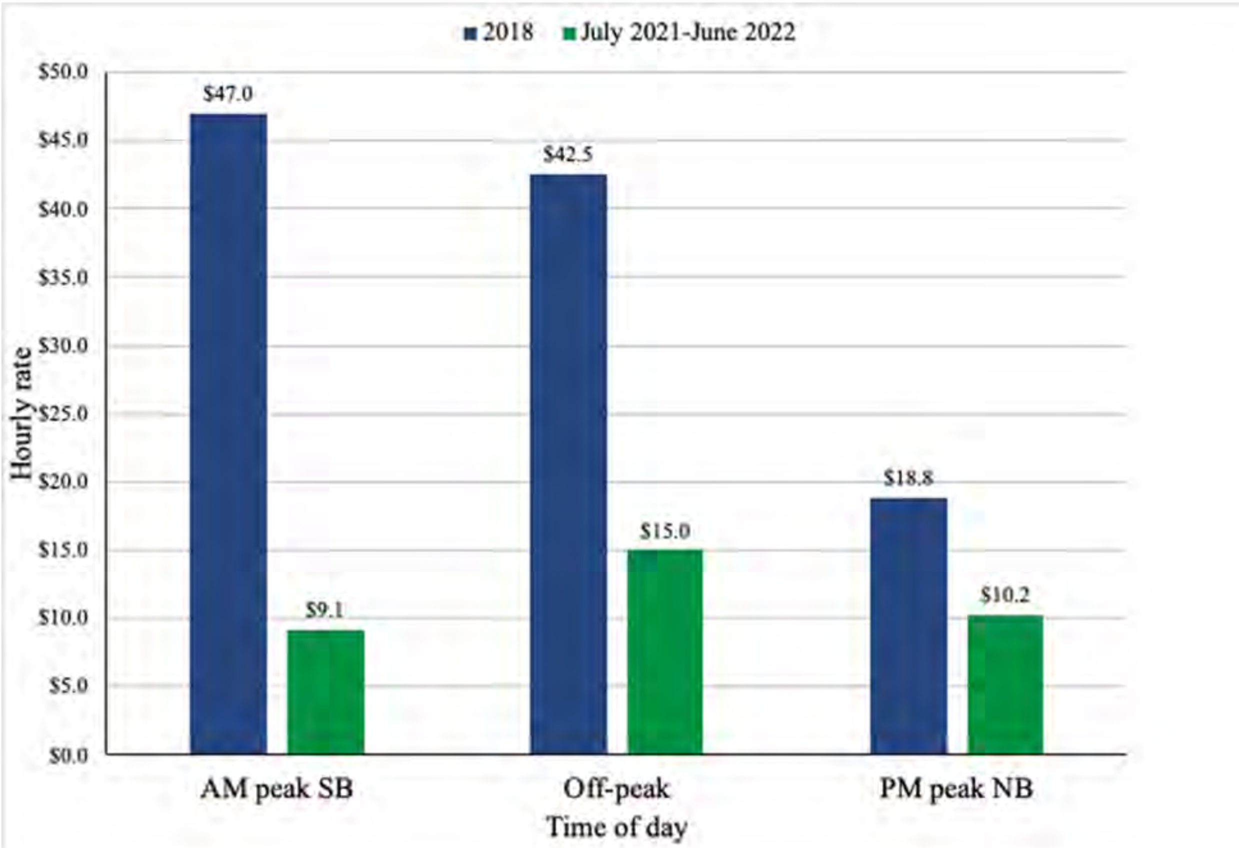


Figure 42: Comparison of Value of Reliability on I-405 ETL, 2018 vs 2021-2022

It is unclear why the VOR dropped so significantly. The primary opinion of the project group is that the decrease in congestion during the peak periods and the improvement in GP reliability resulted in less decision-making emphasis on the historical travel time advantage of the ETLs and more reliance on what current traffic conditions. That is, in 2021-2022 drivers experienced more days when the ETL benefits were moderate (in their eyes). Therefore, they were less likely to assume that they would take the ETL before starting their trip and instead waited to see how bad traffic was before making that decision. Survey responses from individual drivers would be necessary to confirm this opinion or to identify alternative reasons for the drop in the observed value of reliability.

Figure 43 shows a comparison of 2018 and 2021-2022 computed price elasticity values. Price elasticity decreased slightly after the pandemic in both the AM and PM peak periods but increased substantially in the off-peak period from -0.3 in 2018 to -0.51 in 2021-2022. This finding is likely due to the reduced congestion severity during the peak periods after the pandemic recovery started and users being less likely to use the ETLs when traffic flow conditions in the GP lanes are good.

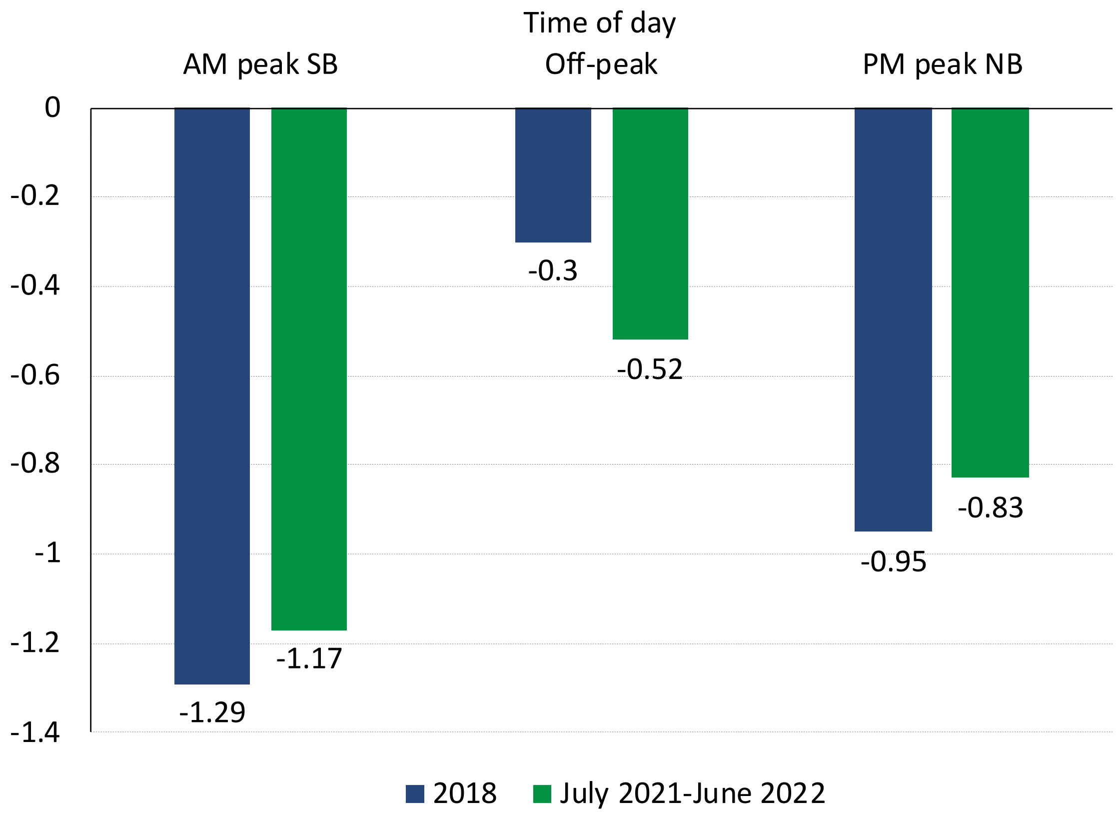


Figure 43: Comparison of Observed Price Elasticity 2018 vs 2021-2022 on I-405

Note that this elasticity estimate applies, on average, only across all trips and times. The marginal price elasticity at a given roadway segment may be quite different, given a certain toll level. In particular, price elasticity at the upper end of the toll scale, near the toll cap of $10, is almost certainly not -0.71.

SR 167 VOT/VOR FINDINGS

One of the intended goals of this project was to compare the value of time, value of reliability, and price elasticities observed on SR 167 with those for I-405. As described in Chapter 3, the SR 167 travel shed serves geographic areas with lower household incomes than those found in the I-405 travel shed. It was therefore of interest to compare the VOT, VOR, and price elasticity between these different travel environments.

Unfortunately, the results from the analysis of SR 167, which used the same types of data and same methodology, were not reliable. Therefore, the project team was unable to make the desired comparison between I-405 and SR 167.

The subsections below describe the SR 167 travel shed, the operation of the HOT lane that is located on SR 167, the performance of the GP and HOT lanes on that facility, and the results of the application of the VOT, VOR, and price elasticity methodology. Additional analyses are also presented that examined the relationships between price and travel behavior in the corridor to determine why the methodology did not produce reliable results as it did for I-405.

Introduction to the SR 167 HOT Lanes

SR 167 is the facility where WSDOT opened its first HOT lane, in May 2008. The HOT lane runs in each direction of SR 167 for approximately twelve miles between Auburn and Renton. Toll rates are based on a variable tolling system, increasing and decreasing with the level of congestion on the highway to ensure that traffic in the HOT lane always flows freely and that carpools enjoy the same fast and reliable trip they have previously experienced in the region's HOV lanes.[15]

There are eight toll gantries in the southbound direction and six gantries northbound. Vehicles are charged the toll observed at the first toll gantry they pass when in the HOT lane, based on the time they pass that gantry. All trips entering the HOT lane at a specific point in time and location pay the same amount, regardless of the distance they travel in the HOT lane. This is unlike toll rates on I-405. The fact that price does not change with distance travelled appears to have some influence on travel behavior, as does the location, intensity, and frequency with which congestion forms in both the GP and HOT lanes.

Figure 44 through 59 visualize roadway performance on SR 167, which in turn influences driver behavior. Figure 44 and Figure 45 illustrate average northbound roadway performance, with Figure 44 showing where and when weekday congestion usually forms in the GP lanes, and Figure 45 showing where congestion forms in the HOT lane.

[15] Washington State Transportation Commission, https://wstc.wa.gov/programs/tolling/sr-167-high-occupancy-toll-lanes/ extracted May 12, 2023

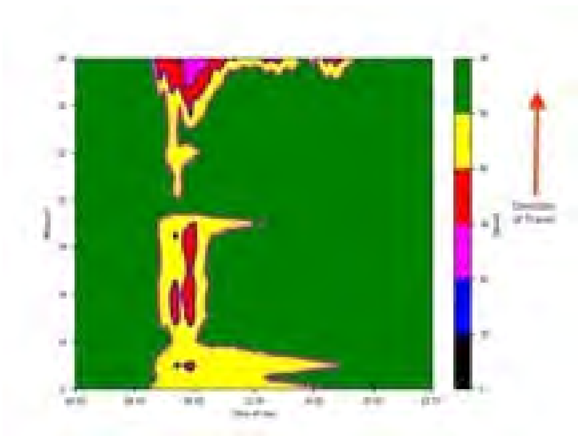


Figure 44: Mean Northbound GP Speed by Location on SR 167

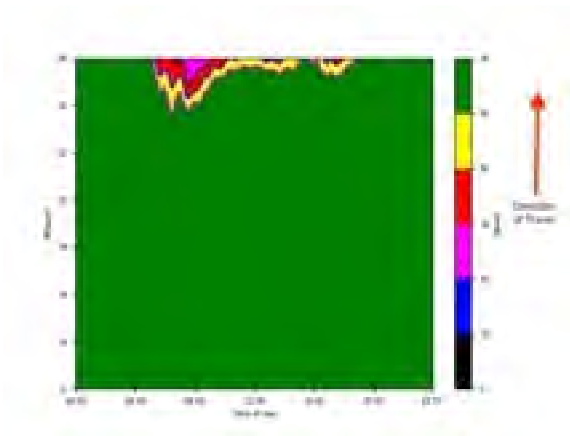


Figure 45: Mean Northbound HOT Speed by Location on SR 167

These figures show that there is modest congestion (yellow color) in the GP lanes during the morning peak period along the length of the corridor, with pockets of more significant congestion (red color) between Auburn and Kent. However, at the northern end of the corridor, backups from the ramps to I-405 significantly affect both the GP and HOT lanes.

An examination of the frequency with which stop-and-go conditions form (Figure 46 shows northbound weekday GP conditions, Figure 47 shows the comparable HOT lane conditions) determined that the longer northbound trips in the corridor's GP lanes experience congestion north of Auburn two to three days a week, with conditions typically easing before the Kent exits. The roadway then breaks down almost every weekday in both the GP and HOT lanes as SR 167 approaches the ramps to I-405.

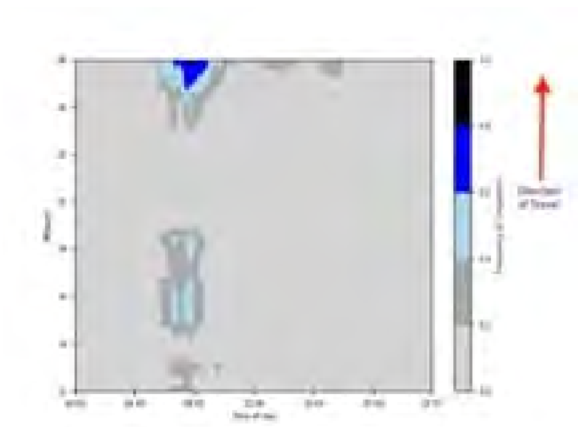


Figure 46: Northbound GP Frequency of Congestion on SR 167

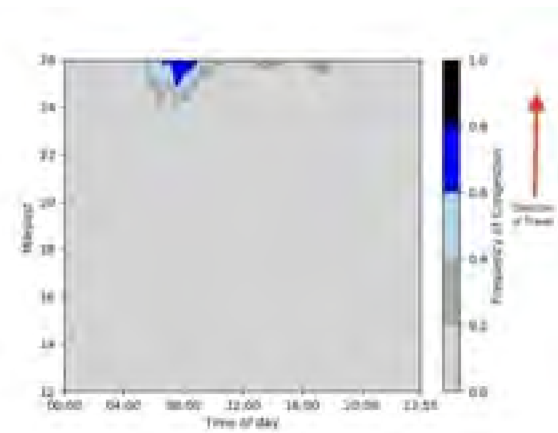


Figure 47: Northbound HOT Frequency of Congestion on SR 167

Southbound traffic conditions are considerably different than those just described for northbound travel. Figure 48 shows the southbound weekday GP lane conditions and Figure 49 shows the corresponding HOT lane conditions. If these graphics are compared to Figure 44 and Figure 45, it can be seen that routine conditions throughout most of the corridor are worse in the afternoon southbound than they are northbound in the morning. In addition, although the southbound HOT lane speeds slow to a modest extent, there is still considerable incentive to use the HOT lane. At the very south end of the corridor, backups occur at the end of the HOT lane in the PM peak period, but unlike the northern AM conditions, the HOT lane backup is considerably smaller and less intense than the GP lane backup. This means that the HOT lane still provides travel time benefits, despite the congestion.

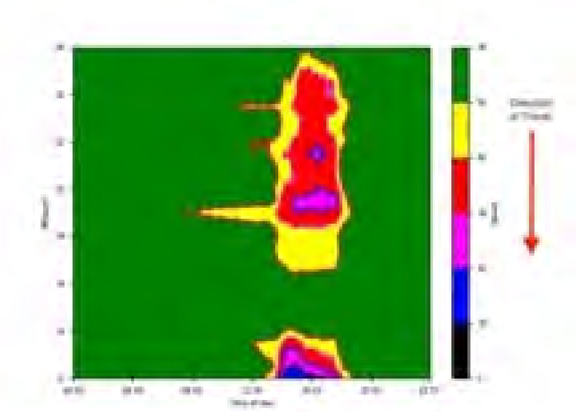


Figure 48: Mean Southbound GP Speed by Location on SR 167

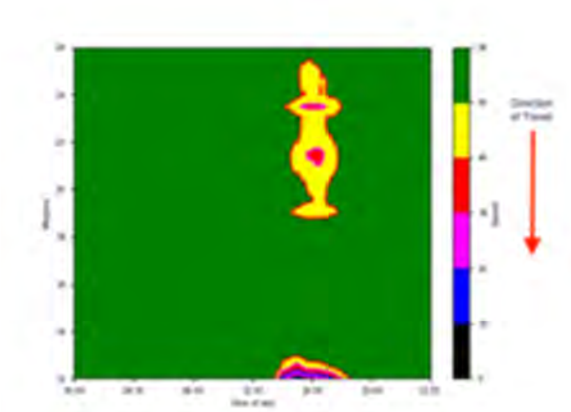


Figure 49: Mean Southbound HOT Speed by Location on SR 167

Figure 50 and Figure 51 show the frequency of stop-and-go traffic on weekdays southbound.

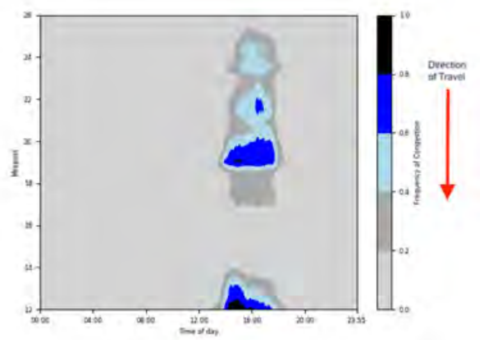


Figure 50: Southbound GP Frequency of Congestion on SR 167

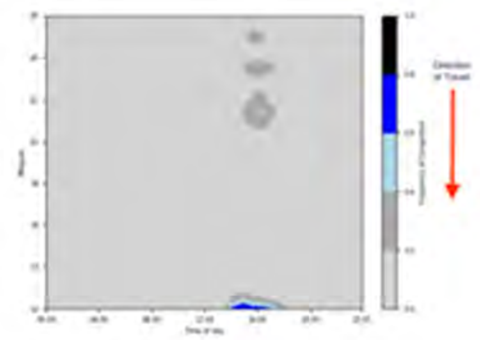


Figure 51: Southbound HOT Frequency of Congestion on SR 167

A comparison of northbound and southbound conditions shows that southbound traffic experiences a very different set of incentives to use the HOT lane over the entire corridor than northbound traffic. For northbound AM peak period users, GP congestion in most of the corridor is modest on many days. This means that many trips have only a modest incentive to use the HOT lane until they reach the congestion forming at the northern end of the corridor, and even then, the benefits to be obtained from using the HOT lane may be small because congestion backing up from I-405 also creates slowdowns in the HOT lane.

Conversely, in the southbound PM peak period, because congestion often forms early in much of the corridor's GP lanes, there is considerable incentive for drivers traveling from I-405 to almost all portions of the corridor to pay to use the HOT lane.

These congestion conditions result in considerably different HOT lane usage choices between northbound and southbound SR 167, and those choices result in very different HOT lane outcomes.

Between July 1, 2021, and June 30, 2022, just over 760,000 travelers paid to use the HOT lanes northbound on SR 167, but more than 895,000 travelers paid to use the southbound HOT lanes. Notably, prices southbound are routinely far higher than northbound prices on most days. The fact that over 130,000 additional travelers pay to use the southbound HOT lanes annually is due to the more significant and more frequent southbound congestion, which provides a greater incentive to use the HOT lanes despite the higher prices. Most of the observed increase in HOT lane demand results from travelers entering the HOT lane at the far northern end of the corridor. Almost 105,500 more paying trips enter at the first gantry southbound than exit from the last gantry northbound. This number increases to over 166,000 if we examine all gantries north of milepost 22 (i.e., that are entrances southbound or exits northbound). Milepost 22 is just south of the first freeway entrances and exits south of the Valley Medical Center.

The increased volumes in the HOT lane southbound not only help determine the routinely higher southbound prices, but they help create modest slowdowns at the northern end of the HOT lane.

If we normalize the origin/destination patterns for the increased volumes in the southbound HOT lane, the entry/exit patterns northbound and southbound are similar but reversed (i.e., entrances northbound become exits southbound). This reveals that the primary differences are caused by the extra volume of trips entering the HOT lane close to I-405 headed southbound. Those additional 130,000 trips shift the overall percentage of vehicles entering from SR 167 in the southbound direction.

Northbound, 62 percent of the HOT lane users enter by the gantry closest to SR 18. In contrast, only 51 percent of southbound traffic exit at or after SR 18. Northbound, 49 percent of HOT lane trips exit at milepost 23. Southbound, just under 55 percent enter by that point on SR 167. Northbound, 48 percent of HOT lane traffic exits near Kent (between mileposts 19 and 22), whereas southbound, 27 percent of the HOT lane traffic enters between mileposts 19 and 22.

Figure 52 and Figure 53 show the mean HOT lane price paid versus the distance of the trip made for both the AM peak period northbound and PM peak period southbound. (The black dots in these graphics show the actual prices paid for each distance on the Y-axis, and the darker the dot, the more often that price was paid for a trip of that distance. The blue line is the mean price paid.) Southbound, longer trips typically pay higher prices. High prices are far less common northbound.

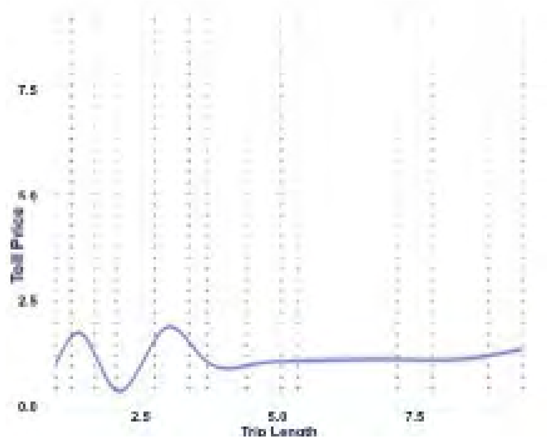


Figure 52: AM Northbound HOT Lane Price vs Trip Length on SR 167

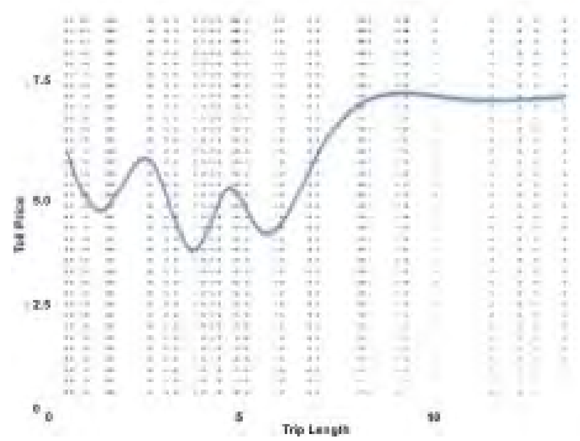


Figure 53: PM Southbound HOT Lane Price vs Trip Length on SR 167

One problem with using these graphics is that northbound HOT lane users traveling between the south end of the facility and Kent (roughly six miles) experience different conditions than travelers entering near Kent and exiting at I-405, even though the trips are of similar length. This difference causes some of the scatter observed in the graphics, as the common price per trip length are different for these trips. (The small dots are the observed data points. The darker the dot, the more times that particular combination of price and trip length occurred, with the blue line representing the mean price.) In contrast, the moderate-length trips southbound (I-405 to Kent) experience fairly heavy congestion whether at the northern end of the facility (I-405 to Kent) or at the southern end of the facility (those entering near Kent and exiting through the end of HOT lane).

Another difference that stands out between these two figures is the much lower price typically paid northbound in the morning (often $2 or less) than that paid southbound in the afternoon (often between $5.00 and $7.50) This shows that demand for the HOT lane northbound is frequently not high enough to increase the price, whereas southbound in the afternoon, sufficient demand frequently exists to substantially raise the price.

One similarity between these figures is that both show a high degree of variation in the price paid for shorter trips, both northbound and southbound, followed by a leveling off of the mean price for longer trips. Northbound, short trips are a combination of trips that enter the HOT lane at the very southern entrance and then exit quickly and those that jump into the HOT lane just before the I-405 back up. Therefore, some of these “short trips” are truly short trips, while others are longer trips during which drivers decline to use the HOT lane for most of the trip until they see a queue form, at which time they jump into the HOT lane and pay the toll. Southbound short trips mostly enter the HOT lane at the northern end of the corridor and exit SR 167 mid-corridor. The biggest difference between northbound and southbound is the price paid.

While both graphics show dips in the mean price paid for some shorter trips, Figure 52 shows that very few travelers choose to enter the HOT lane roughly 2 miles before the end of the HOT lane. This corresponds to the portion of the corridor that approaches the location where the backups to the I-405 ramps begin. This illustrates a location where travelers often find little value in paying for the HOT lane, even at a low price, because the HOT lane is as congested as the GP lane.

These travel conditions explain some of the differences in the estimates of the value of time that are described below, as well as how those estimates differ from those observed on I-405.

Computed Value of VOT, VOR, and Price Elasticity

The values of time and reliability for SR 167 as a whole, computed with the same technique used for I-405, are shown in Table .

Table 7: Summary Values of Time and Reliability for All Movements on SR 167

Statistic	**Value**
Value of Time (VOT)	$47.5 / hr
Value of Reliability (VOR)	-$13.0 / hr
Price Elasticity	0.400

In comparison, the values computed for I-405 in 2021-2022 were $56.6/hr VOT, $14/hr VOR, and an elasticity of -0.71 (meaning a 10 percent toll increase would lead to a 7.1 percent decrease in volume).

While the value of time computed for SR 167 ($47.5/hr) made some sense (it could be argued that the lower household income levels of the communities that use SR 167 have a lower value of time than the higher income neighborhoods that more frequently use I-405 in the north end), the negative value of reliability and the fact that elasticity was positive made little sense and called into question the results. (That is, why would drivers pay less for a reliable trip, and why would HOT entrance volumes increase when price increases?) These results led the project team to examine a variety of different model formulations to take into account the different behavioral aspects of the corridor. Unfortunately, we were not able to develop a model that effectively described value of time and reliability for the corridor as a whole.

To try to develop a more useful model, the project team split the analysis to look separately at the AM northbound and PM southbound directions because the travel conditions observed in those two movements are so different. Running the VOT and VOR calculations for the AM northbound peak movements separately from the PM southbound movements, as well as for all off-peak time periods, resulted in the outcomes shown in Table 8.

Table 8: Value of Time Results by Peak Movement on SR 167

	PM Southbound	AM Northbound	Off-peak
Value of Time (VOT)	$59.9 / hr	-$203.0 / hr	$61.7 / hr
Value of Reliability (VOR)	-$12.1 / hr	-$114.0 / hr	-$10.3 / hr
Elasticity	0.818	0.565	0.256

Unfortunately, these results made even less sense than the corridor-wide values shown in Table 7.

Discussion

To try to understand why the model results were not reasonable, the project team developed graphics to describe HOT lane decision-making behavior in the corridor. Figure 54 shows the relationship between the price paid by HOT lane users (the X-axis) and the time saved (the Y-axis) northbound in the morning peak period. Figure 55 shows this same information for the PM peak in the southbound direction.

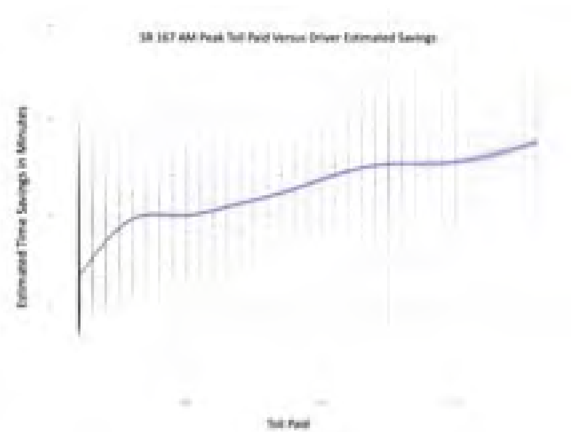


Figure 54: AM NB Time Saved Versus Price on SR 167

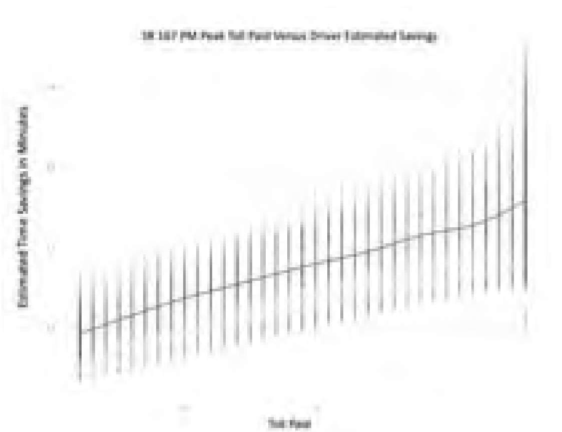


Figure 55: PM SB Time Saved Versus Price on SR 167

Given these two graphics, the project team's expectation was that the VOT for both AM and PM peaks would be positive because of the positive trend, but SR 167 AM peak VOT in the original value of time model was negative. The negative value appeared to be the result of the very large variation in time savings found at the minimum price combined with the very large number of low-price trips that occur in the AM peak period. (Note the large black line on the far left of Figure 54, which is not the Y-axis of the graph but instead shows that actual time savings vary dramatically for travelers paying the minimum price, with many users saving large amounts of time and others saving very little.)

Figure 55 is the same graphic but for the PM peak, southbound trip rather than the AM northbound trip. Like Figure 54, this graphic shows a positive upward trend. Unlike the AM peak movements, however, the value of time is positive for the PM peak southbound movement. A comparison of the two graphics shows that the variation in time savings at the minimum price is much smaller southbound in the evening, and the number of times that the minimum price is paid is much smaller. The greatest variation in time savings for a given price is at the extreme right of the graphic, where price is highest and time savings, even at their smallest, are still large.

The other major difference is that Figure 55 shows a very linear relationship, whereas the relationship in Figure 54 changes significantly with price. Time savings initially rise quickly with price. They then level off, then drop slightly before increasing at a low linear rate, then flatten again, and finally rise once more. The lack of consistency in the relationship between price and time savings in the morning reflects traveler decision making, as values of time and reliability are inconsistent, suggesting that in many cases motorists choose to use the HOT lane—at minimum price—for reasons other than expected time savings when they make the decision. The lack of a consistent relationship—and the lack of frequent, sizable HOT lane time savings—also appear to be a potential cause for the lack of value of travel time reliability, at least as measured in the relationship between the 50^{th} and 80^{th} percentile travel times. However, at higher toll prices, drivers appear to respond in a manner more aligned with expected economic behavior.

The next set of graphs compares the number of travelers who choose to pay to enter the HOT lane during any given one-minute period (the Y-axis) and the price they pay to do that (the X-axis). Graphics are shown for AM northbound on SR 167, PM southbound on SR 167, and the corresponding peak period, peak direction movements on I-405.

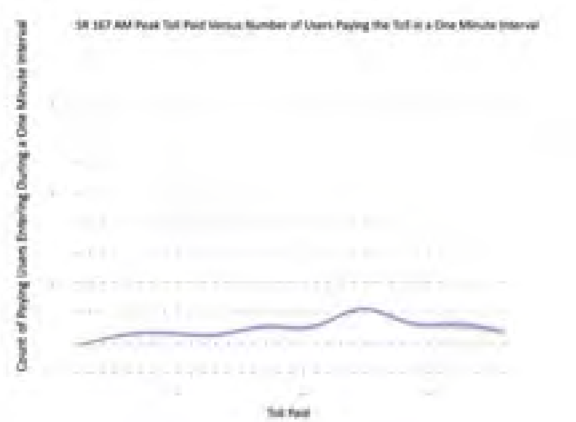


Figure 56: Entering Motorists by Price AM NB on SR 167

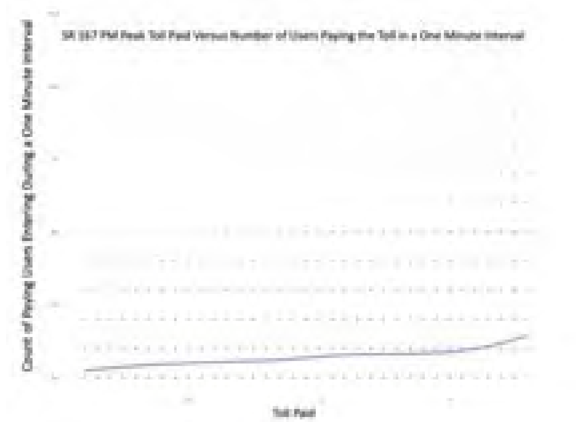


Figure 57: Entering Motorists by Price PM SB on SR 167

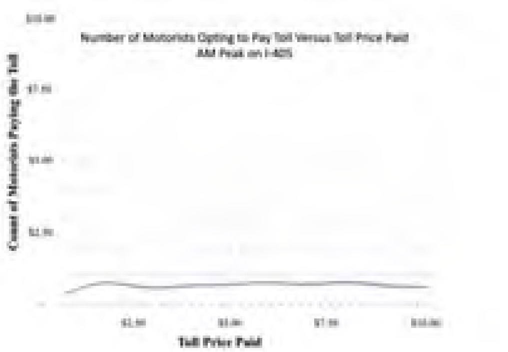


Figure 58: Entering Motorists by Price - AM Peak on I-405

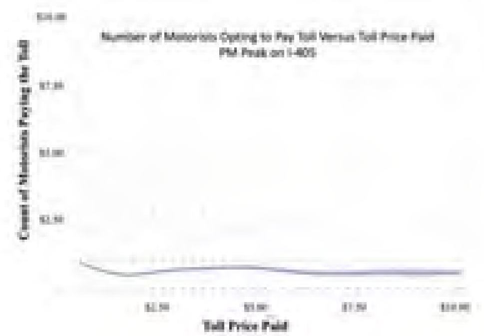


Figure 59: Entering Motorists by Price - PM Peak on I-405

In these four graphs, the curves that illustrate traveler behavior on SR 167 have shapes different from those for I-405 with respect to the impact of increasing toll prices. In a dynamic toll environment, prices rise to decrease the incentive to use the HOT lane. Increasing congestion in the GP lanes provides the counterpoint to price. Ideally, in the peak period, the HOT lane operates just under capacity, with a fairly constant number of vehicles entering the facility, keeping it full but not too full. This maximizes use of the facility, achieving the roadway's operational goal. Figure 58 and 58 show that this is being achieved on I-405. The number of entering vehicles is fairly constant across the entire price scale, with modest differences at the points where price first rises above the minimum. (In the AM on I-405, increasing prices at the minimum value appear to be a signal to drivers to quickly jump in before the price rises further. In the PM on I-405, motorists appear to be trying to take advantage of the minimum price in expectation of worsening conditions, and intake quickly reaches a constant value.)

On SR 167, behavior is very different. During the morning commute (Figure 56) increasing the price initially causes an increase in the number of motorists willing to pay. This increasing trend then reverses as price reaches about $6, when the number of new HOT lane users willing to pay declines as price continues rising. The pattern is again different in the more congested afternoon peak period. In the afternoon (Figure 57), increasing the price causes even more willingness to pay. Motorists who enter early in the corridor appear to use the high price as a signal that congestion is worse than usual, and they are thereby even more willing to pay to avoid it.

Both of these behaviors are very different than those observed on I-405, and both suggest that factors other than the value of time and value of reliability significantly affect the choice to pay or not pay on SR 167.

As result, the research team concluded that the technique developed in the 2019 study for HOT lane equity analysis is not effective at capturing the pricing behavior found on SR 167. It is unclear whether the major causes of these differences in behavior are

- the “free entry/exit” policy on SR 167 in comparison to the limited entry/exit policy on I-405,
- the fact that prices on I-405 frequently differ with distance traveled, whereas they are constant on SR 167—leading to very different price/time savings relationships, or
- the more highly variable traffic conditions on SR 167 and frequently lower levels of congestion, especially in the northbound movement.

Additional study is needed to better model these relationships.

Chapter 4. Conclusions and Recommendations

CONCLUSIONS

This project developed numerous findings from the analysis of large amounts of data. The most significant of these findings are as follows:

- The use of tolls to pay for at least a portion of the cost of very expensive roads in Western Washington does provide some equity benefit. It shifts at least some of the cost of those roads to the wealthier portion of the state and away from lower-income residents in the eastern portions of the state by shifting a portion of the cost of those roads away from general transportation taxes and to direct user fees.
- This does shift some of that burden to lower-income residents in the western part of the state, especially those who live near the toll facilities, given that these roads serve the travel patterns in those areas better than most alternatives. Where these tolls can be easily avoided (e.g., the HOT lanes on SR 167 and I-405) the equity outcomes of this decision should be considered good, as lower-income households have reasonable alternatives, and drivers who choose to pay those tolls typically gain value for their payments. Where tolls cannot be easily avoided (e.g., the Tacoma Narrows Bridge on SR 16), it is necessary to more carefully weigh the benefits that individual households gain from the facility versus the shift of the cost burden to those households. This benefit/cost comparison was outside the scope of this project.
- The environmental "costs" (primarily noise and air pollution) of living near these facilities also is part of an equity analysis. However, evaluating those costs to neighborhoods and comparing them to the benefits obtained through the improved access to opportunity that the toll facilities provide was also outside the scope of this project. Nevertheless, these calculations should be included in equity analyses for new toll facilities being considered.
- Among Western Washington residents, higher-income households are more likely to pay tolls and thus make comparatively fewer toll avoiding trips than moderate-

and lower-income households. This further shifts the cost of the toll facilities to households more able to pay for those facilities.

- Not surprisingly, the profiles of users of toll facilities and their use of each facility are greatly influenced by the demographics of the travel sheds the roads serve.
- Higher-income households, as indicated by the regional population profile, are typically over-represented on the toll facilities. The one exception is on SR 16. This is due in large part to the fewer higher-income households that live north of the Tacoma Narrows Bridge, where many frequent bridge users reside.
- Moderate-income households are particularly well represented on the southern toll facilities (SR 16, SR 167), again in large part due to the demographic profile of that portion of the Puget Sound region.
- Higher-income households are significantly over-represented on SR 520, in large part because its travel shed contains large numbers of high-income neighborhoods. The SR 520 bridge user population is essentially the opposite of the SR 16 bridge user population, with a much larger number of higher-income users and much small number of low- and lower-middle income populations.
- The observed value of time for those who pay to use the I-405 Express Toll Lanes has increased modestly since 2018, whereas the value that those drivers place on reliability has decreased substantially. These changes may be due to a decrease in the observed levels of congestion in both the I-405 GP and HOT lanes.
- The analytical technique that was used to determine the value of time, value of reliability, and price elasticity for I-405 did not produce reliable statistics for SR 167.
- While it is unclear exactly why the technique failed for SR 167, several things are clear from a detailed analysis of the toll transaction and roadway performance data, including the following.
    - Because of drivers' ability to enter the SR 167 HOT lane whenever they desire versus the limited entry/exit options on the I-405 Express Toll Lanes, driver decision making associated with the HOT lanes is different, and the data used for the statistical analysis may not adequately model conditions on SR 167 at the actual decision points like they do on I-405.

- Another major difference between the two facilities is that on SR 167 the price paid is not affected by the distance traveled in the HOT lane, whereas distance does play a factor on I-405. Longer trips on I-405 are typically the most expensive but also provide the largest time savings. The result is very different price/outcome relationships for many northbound AM trips on SR 167 versus what on I-405. This may well affect the observed values of time and reliability on SR 167.
- On SR 167, congestion conditions northbound in the morning peak period are very different than those southbound in the afternoon peak period.
- On SR 167, the much lower levels of morning congestion result in much lower levels of HOT lane use and consequently much lower HOT lane prices.
- On SR 167, the low morning prices and much higher afternoon prices for use of the HOT lanes, combined with the size of routine congestion and locations of where it forms in the morning and afternoon, appear to generate very different travel behavior patterns among drivers. Those different behaviors appear to generate very different values of time, reliability, and price elasticity for these movements on SR 167.

RECOMMENDATIONS FOR NEXT STEPS

While the analyses conducted with anonymized toll transaction and LBS data were very useful in describing behavior in numeric terms, these statistical analyses are not able to explain decision-making behavior. The UW team recommends that WSDOT conduct a survey of WSDOT toll account holders that asks to monitor their use of the facility and asks questions about their decision-making process regarding when they choose to use, or not use, toll facilities. Such a project would require permission from participants to use their identified data, and it would likely require renumeration to those users, thereby limiting sample size. However, it would generate data on the specific decision-making processes that are not available from anonymized data. It would also allow the collection of confirmed household income data, which would help validate the results of the statistical approaches used in this and previous WSDOT studies.

For example, this future study could examine the degree to which (or even whether) moderate-income facility users are relatively insensitive to the lowest toll prices on the HOT lane. Or if this insensitivity occurs only in higher-income households. In addition, it would be possible to determine why drivers choose to use the HOT lane when little travel time benefit would be gained.

It is recommended that such a study be constrained to one (SR 167) or at most two (SR 167 and SR 99) corridors, as both those corridors have more modest user income distributions than I-405 or SR 520 and more travel options than SR 16. These roadways present the best opportunity to gain the most insight into travel behavior that best reveal the impacts of tolls on travel equity.

The second recommendation for future work is to design and conduct a study that is specifically directed at understanding the impacts of geography on toll facility use, avoidance, and equity. For example, it might use PSRC's regional models for peak and off-peak traffic conditions to determine origin/destination pairs likely to experience both toll and toll-avoidance behavior. Then travel time data could be collected for actual toll and non-toll travel options for those O/D pairs from navigation websites for a large number of days. These independent toll/no-toll travel time comparisons could then be used as independent variables for input into an analysis of actual O/D travel behaviors observed in LBS data to determine the impacts that day-to-day changes in traffic congestion have on decision making. The intent would be to answer questions such as, "To what degree does bad congestion on I-5 drive use of SR 99? To what extent is that behavior geography driven? To what extent is it income driven? Can values of time and reliability be determined from that observed travel behavior, given measurements of toll/no-toll travel time for non-HOT lane toll corridors?"

Chapter 5. References

Brent, Daniel A., and Austin Gross. 2018. "Dynamic Road Pricing and the Value of Time and Reliability." Journal of Regional Science 58 (2): 330–49. https://doi.org/10.1111/jors.12362

Eksler, V., S. Lassarre, and I. Thomas. 2008. "Regional Analysis of Road Mortality in Europe." *Public Health* 122 (9): 826–37. https://doi.org/10.1016/j.puhe.2007.10.003.

ESRI. 2022. "Data Classification Methods—ArcGIS Pro | Documentation." Data Classification Methods. 2022. https://pro.arcgis.com/en/pro-app/latest/help/mapping/layer-properties/data-classification-methods.htm.

Gelman, Andrew, David K. Park, Stephen Ansolabehere, Phillip N. Price, and Lorraine C. Minnite. 2001. "Models, Assumptions and Model Checking in Ecological Regressions." *Journal of the Royal Statistical Society: Series A (Statistics in Society)* 164 (1): 101–18. https://doi.org/10.1111/1467-985X.00190.

Goodman, Leo A. 1959. "Some Alternatives to Ecological Correlation." *American Journal of Sociology* 64 (6): 610–25. https://doi.org/10.1086/222597.

Greenland, Sander, and Hal Morgenstern. 1989. "Ecological Bias, Confounding, and Effect Modification." *International Journal of Epidemiology* 18 (1): 269–74. https://doi.org/10.1093/ije/18.1.269.

Greenland, Sander, and James Robins. 1994. "Invited Commentary: Ecologic Studies—Biases, Misconceptions, and Counterexamples." *American Journal of Epidemiology* 139 (8): 747–60. https://doi.org/10.1093/oxfordjournals.aje.a117069.

Jackson, Christopher. 2006. "Ecoreg Guide." MRC Biostatistics Unit, Cambridge.

Kammoun, Karim, Aymen Ghédira, Chaker Ben Saad, and Nesrine Bouhamed. 2020. "Analysis of Road Mortality in Digital Age Using Bayesian Ecological Model: The Case of Tunisia." *World Review of Intermodal Transportation Research* 9 (4): 393–409. https://doi.org/10.1504/WRITR.2020.111063.

Kuai 2020Kuai, Xuan, and Fahui Wang. 2020. "Global and Localized Neighborhood Effects on Public Transit Ridership in Baton Rouge, Louisiana." Applied Geography 124 (November): 102338. https://doi.org/10.1016/j.apgeog.2020.102338.

Leung, Shirley, McCartan Cory, Robinson CJ, Roshan Zamir Kiana, Hallenbeck Mark, and Iverson Vaughn. 2019. "I-405 Express Toll Lanes: Usage, Benefits, and Equity." University of Washington eScience Institute.

Lou, Yin, C. Zhang, Y. Zheng, X Xie, W. Wang, and Y Huang, "Map-matching for low-sampling-rate GPS trajectories," *Proceedings of the 17th ACM SIGSPATIAL international conference on* *advances in geographic information systems*. 2009. https://dl.acm.org/doi/10.1145/1653771.1653820

Prentice, Ross L., and Lianne Sheppard. 1995. "Aggregate Data Studies of Disease Risk Factors." *Biometrika* 82 (1): 113–25. https://doi.org/10.1093/biomet/82.1.113.

Richardson, Sylvia, and Christine Monfort. 2000. "Ecological Correlation Studies." *Spatial Epidemiology: Methods and Applications*, 205–20.

Richardson, Sylvia, Isabelle Stücker, and Denis Hémon. 1987. "Comparison of Relative Risks Obtained in Ecological and Individual Studies: Some Methodological Considerations." *International Journal of Epidemiology* 16 (1): 111–20. https://doi.org/10.1093/ije/16.1.111.

Small, Kenneth A., Clifford Winston, and Jia Yan, "Uncovering the Distribution of Motorists' Preferences for Travel Time and Reliability," Econometrica, 2005, 73 (4), 1367–1382

Wakefield, Jonathan, and Ruth Salway. 2001. "A Statistical Framework for Ecological and Aggregate Studies." *Journal of the Royal Statistical Society: Series A (Statistics in Society)* 164 (1): 119–37. https://doi.org/10.1111/1467-985X.00191.

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