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Pricing and Travel Time Reliability Enhancements in the SANDAG Activity-Based Travel Model: Final Report

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1.0   INTRODUCTION

This report describes the work undertaken under the SANDAG On-Call Modeling Services Task Order 17 designed to enhance the San Diego Association of Governments (SANDAG) activity-based model's sensitivities to priced infrastructure and travel time reliability. The SANDAG activity-based model is a member of the Coordinated Travel – Regional Activity-based Modeling Platform (CT-RAMP) family of models in use by many large Metropolitan Planning Organizations in the United States. The model system includes a detailed representation of space, stop-to-stop transit utility calculations, and was recently updated to include an all-streets representation of walk and bike accessibilities (Davidson et al, 2010). The model is applied to a fully-attributed synthetic population of San Diego residents and includes disaggregate tour-based model components for non-resident overnight visitors, Mexican residents, internal-external trips, and airport trips.

This project focused on enhancements related specifically to the model's ability to accurately represent demand on current and future toll and high-occupancy toll lanes. The enhancements implemented during this project are based upon recent federal research conducted under the Strategic Highway Research Program (SHRP) 2 C04 track to improve our understanding of how highway congestion and pricing affect travel demand. The research culminated in a technical report (Parsons Brinckerhoff et al, 2013), referenced heavily in the following pages. The SHRP L03 project "Analytical Procedures for Determining the Impacts of Reliability Mitigation Strategies" (Cambridge Systematics, Inc.,Texas A&M Transportation Institute, University of Washington, Dowling Associates, Street Smarts, Herb Levinson, Hesham Rakha 2013) is also referenced.

Our work resulted in the following general conclusions (more information can be found throughout the document and in the summary chapter):

- It was relatively straight-forward to implement many of the SHRP C04 recommendations, partly due to the flexible structure of the SANDAG activity-based travel model software. Inclusion of three value-of-time bins for auto modes increased skimming and assignment time by approximately one hour per iteration, and tripled the amount of memory required for storing skims.

- The analysis of INRIX travel time data for the San Diego region resulted in reasonable relationships between travel time variability and network characteristics including demand. The enhanced models use standard deviation of travel time in both skimming and assignment, and travel time reliability is taken into account in mode choice (and influences other decisions through logsums). However, significant practical research is needed to both analyze travel time reliability and incorporate reliability into network assignment models in a theoretically consistent way.

- The enhanced models have been shown to match observed demand on existing toll roads in San Diego better than the previous model, and demonstrate reasonable elasticities to changes in toll cost. We find that accurate representation of toll entry\exit points and costs, and inclusion of a toll transponder ownership model to constrain demand, are important features of the revised model system.

We believe that this research is a valuable contribution to the modeling community. This research is particularly applicable to the large number of metropolitan regions that have developed or are developing activity-based travel demand models, and who are interested in analyzing priced highway lanes as a tool to manage congestion, increase mobility options, and raise revenue for transport investments. Many of the recommendations and enhancements in this report are ready for implementation and do not require large investments in hardware or software, and do not increase runtime beyond reasonable time-frames for most regional analysis.

This document proceeds as follows. The first section summarizes relevant recommendations from the SHRP C04 and SHRP L03 report. The next section describes the data available for model development. Details about any data processing are also included. The next two sections place the recommendations summarized in first section into context given the existing CT-RAMP model framework and describes steps performed to implement the enhancements, including scripting and software development. Run time impacts of the model enhancements are also discussed. The next section describes two sensitivity tests that the project team performed to ensure that the model system behaves appropriately given changes in inputs and available data. The final section summarizes problems encountered and lessons learned during the project. Benefits of this work to SANDAG or other similar agencies are also discussed in the section.

2.0 SHRP2 C04 RECOMMENDATIONS

The SHRP2 C04 report analyzed traveler sensitivity to highway pricing and congestion under a range of travel choice dimensions (generation, distribution, time-of-day, mode choice, and route choice) using several stated and revealed preference datasets. The report found several consistent features of response to congestion and pricing and developed a general equation (Equation 1) to describe highway utility based upon these findings.

EQUATION 1: GENERALIZED COST FUNCTION FOR HIGHWAY UTILITY

$$U = \Delta + a_1 \times Time \times (1 + a_2 \times Dist + a_3 \times Dist^2) + b \times \left[Cost / (Inc^e \times Occ^f) \right] + c \times STD / Dist$$

Where:

Δ	=	Alternative-specific "bias" constant for priced facilities
a_1	=	Travel time coefficient, estimated as a random parameter to capture unobserved user heterogeneity
$Time$	=	Average travel time
a_2, a_3	=	Coefficients reflecting the impact of travel distance on perception of travel time
$Dist$	=	Average travel distance
b	=	Coefficient on travel cost
$Cost$	=	Cost of travel including tolls, parking, and auto operating costs
Inc	=	Household income of traveler
e	=	Coefficient reflecting the impact of income on the perception of cost
Occ	=	Occupancy of vehicle
f	=	Coefficient reflecting the impact of auto occupancy on the perception of cost
c	=	Coefficient reflecting the impact of travel time (un-)reliability
STD	=	Day-to-day standard deviation

The formula has several interesting features. First, the report recommends a random coefficient on travel time to reflect unobserved user heterogeneity. The advantage of a distributed coefficient on travel time is to overcome aggregation bias associated with using an expected mean travel time coefficient. The report recommends a truncated lognormal distribution such that values of the coefficient are constrained to be negative, thus ensuring a logical negative utility response with respect to travel time. Research indicates that the distribution of travelers by value-of-time is positively skewed; that is, there are travelers with a relatively high willingness-to-pay compared to the mean. The use of a distributed travel time coefficient should improve the ability of the travel demand model to predict the aggregate response to priced transport facilities such as managed lanes.

The report recommends truncating the distribution to ensure a reasonable mean travel time coefficient and eliminate the possibility of extreme insensitivity to time at the tail of the distribution. The report provides a graph of sample travel time distributions but does not recommend specific parameters. However, RSG

recently implemented random travel time parameters in the Sacramento Association of Governments SacSim activity-based model based upon the C04 report recommendations (Mark Bradley 2015). The authors use a coefficient of -0.03 times a random value drawn from a lognormal distribution with mean 1.0 and standard deviation 0.8 for work tours, and a coefficient of -0.015 times a random value drawn from a lognormal distribution with mean 1.0 and standard deviation 1.0.

The formula for a lognormal probability density function is given in Equation 2. Figure 1 shows the resulting probability density functions for work and non-work time coefficients.

EQUATION 2: PROBABILITY DENSITY FUNCTION FOR LOGNORMAL DISTRIBUTION

$$fx(x; \mu, \sigma) = \frac{1}{x\sigma\sqrt{2\pi}} e^{-\frac{\ln(x-\mu)^2}{2\sigma^2}}, \qquad x > 0$$

Where:

X = a log-normally distributed variable

μ = the lognormal distribution location parameter; specifically, the mean of ln(x)[1]

σ = the lognormal distribution scale parameter; specifically, the standard deviation of ln(x)[2]

FIGURE 1: PROBABILITY DENSITY FUNCTIONS FOR WORK AND NON-WORK TRAVEL TIME COEFFICIENTS
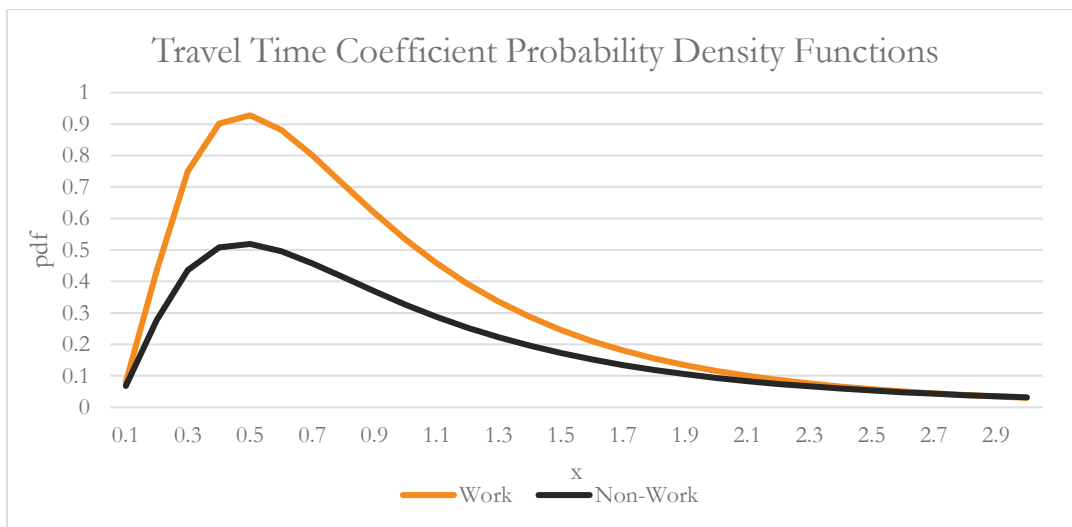
Second, the recommended highway utility function suggests that travel time sensitivity should be a function of distance. Figure 2 shows the distribution of travel time sensitivity across a range of distances, using the recommended parameters for travel to and from work from the report. The recommended parameters result

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[1] The location parameter μ can be calculated by the following formula, where m is the non-logarithmic mean and v is the non-logarithmic variance of the distribution: $\mu = ln\left(\frac{m}{\sqrt{1+\frac{v}{m^2}}}\right)$

[2] The scale parameter σ can be calculated by the following formula: $\sigma = \sqrt{ln\left(1 + \frac{v}{m^2}\right)}$

in a range of sensitivity that is equal to travel time coefficient at very short distances, increasing up to a range of approximately 34 miles where travelers are approximately 1.4 times as sensitive to travel time as at short ranges. The recommended parameters decrease after 34 miles, until travelers are approximately 0.7 times as sensitive to travel time at 80 miles as at very short distances.

The report posits several explanations for the non-linear distance effect observed in the estimation results, such as a potential underlying correlation between rail mode travel and long trip distances, which might result in a less onerous travel time coefficient at longer distances. Another explanation offered for the non-linear effect is that travelers may compensate for longer work travel times by increased telecommuting, which might manifest as a lower travel time coefficient for longer distances. However, note that other studies, particularly those using stated preference survey data on long distance travel choices (Peter Burge 2011), have shown increasing values of time with respect to trip distance. Therefore, we did not implement distance-based travel time sensitivities in the SANDAG CT-RAMP system at this time.

FIGURE 2: SHRP C04 DISTANCE-BASED FACTOR ON TRAVEL TIME SENSITIVITY
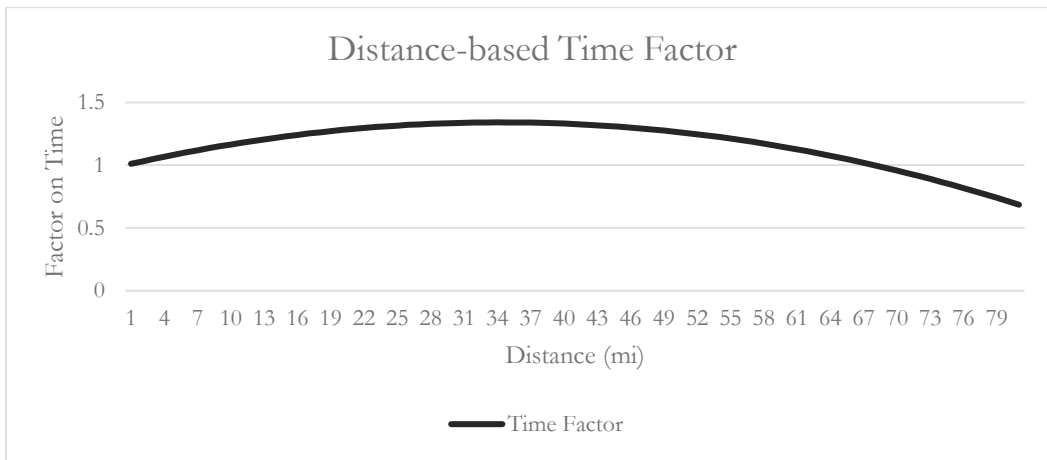
Third, the C04 report recommends scaling the travel cost coefficient by a function of household income and auto occupancy. The report suggests scaling the cost coefficient by household income raised to a power between 0.6 and 0.8 and by auto occupancy raised to a power of between 0.7 and 0.8. Figure 3 shows the effect of scaling the cost coefficient by household income, in relation to the cost coefficient for a traveler from a household earning $65,000 (median household income for San Diego County was approximately $63K according to 2008 to 2012 American Community Survey data). The graph shows that travelers from very low income households are between 3.5 and 4.5 more sensitive to travel cost than travelers from $65k households, and that travelers from households earning $200k are approximately half as sensitive to cost as travelers from $65k households.

FIGURE 3: EFFECT OF SCALING COST COEFFICIENT BY HOUSEHOLD INCOME
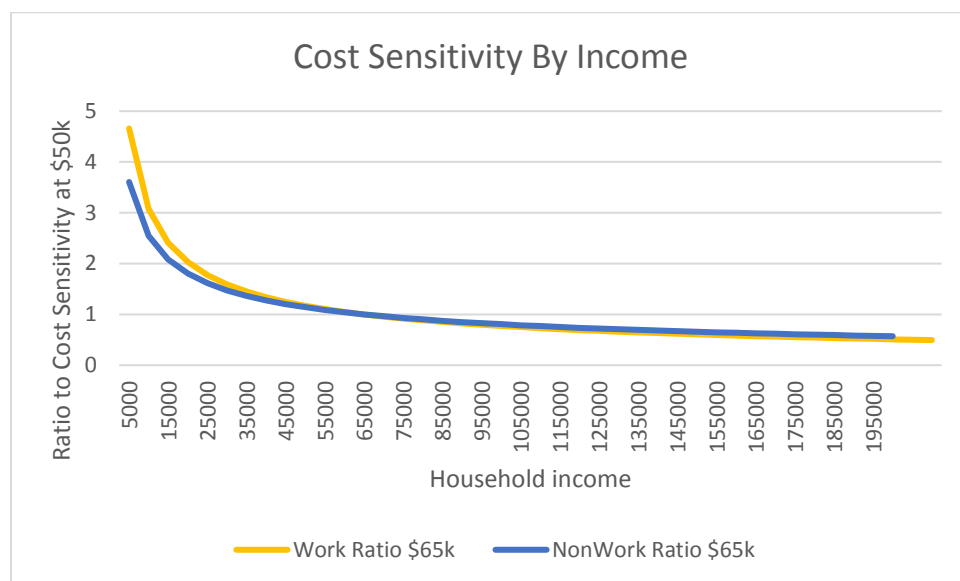
The suggested factor on auto occupancy results in a further scaling of cost by approximately 1.7 for two person shared-ride tours and approximately 2.2 for three-plus person shared-ride tours. These ranges seem reasonable given that the majority of shared-ride tours are between members of the same household, where cost sharing across carpool members is less likely.

Finally, the highway utility function recommended in the C04 report includes a term on the standard deviation of travel time, scaled by distance (unit deviation), as a measure of reliability. The coefficient on the reliability term is negative, reflecting the increased cost of schedule delays due to unreliable travel times and the need to plan 'buffer' time in one's activity schedule. The term is logical as scaling by distance reduces correlation with other components of highway utility and the standard deviation of travel time is a reasonable estimate of reliability. However, the standard deviation of travel time cannot be directly measured by an equilibrium highway assignment model due to its convergence properties. A dynamic traffic assignment (DTA) model is required in order to apply this function as recommended, where the standard deviation of travel time can be measured across multiple assignment simulations where inputs are varied to represent real-life daily fluctuations in demand, weather, incidents, and other factors.

While SANDAG is developing a dynamic traffic assignment model under a separate project, it is not available for this study. In lieu of a DTA model, the C04 report suggests the possibility of using travel time by level of congestion as a proxy for reliability. This approach may be reasonable given that unreliability of travel time tends to increase with respect to traffic congestion, as typical volume-delay functions become very steep at relatively high volume to capacity ratios. Any small change in traffic conditions can therefore have relatively large effect on travel time. Table 1 shows travel time reliability proxy factors by travel conditions recommended in the C04 report. The table shows asserted volume to capacity (v\c) ratios that may be used to differentiate each link by travel condition for the purposes of creating weighted travel time skims. This approach may be reasonable given that unreliability of travel time tends to increase with respect to traffic congestion. However, our analysis of reliability data for San Diego indicates that periods of unreliability vary within the five assignment periods used in the travel model, which leads us to believe that factors based only on volume to capacity ratio may simply double-count congestion.

TABLE 1: RECOMMENDED TRAVEL TIME RELIABILITY PROXY FACTORS

Travel Conditions	V\C Ratio (Asserted)	Weight
Free-flow	0.00-0.59	1.00
Busy	0.60-0.69	1.05
Light Congestion	0.70-0.79	1.10
Heavy Congestion	0.80-0.89	1.20
Stop Start	0.90-0.99	1.40
Gridlock	1.00+	1.80

It may also be possible to estimate the standard deviation of travel time using methods proposed by the SHRP L03 project (Cambridge Systematics et al, 2013). In this project, the authors develop equations that estimate the mean and standard deviation of Travel Time Index (TTI), which is a measurement of the ratio of free-flow speed to actual speed for a given section of roadway (Equation 3). The authors note in an appendix that if the space mean speed is measured from a travel model, the equation measures 'Recurring Mean TTI', which then must be converted to Mean TTI to account for non-recurring congestion using Equation 4. The equations for the 'data-poor' model simply measure mean and standard deviation of travel time index based upon facility type, though the report only provides an equation for standard deviation of TTI for urban freeways (Equation 5).

EQUATION 3: TRAVEL TIME INDEX (TTI)

TTI = Max (1.0, Free-flow speed/Space mean speed)

EQUATION 4: MEAN TTI BASED ON RECURRING MEAN TTI

$MeanTTI = 1.0274 \times RecurringMeanTTI^{1.2204}$

EQUATION 5: STANDARD DEVIATION OF TTI FOR URBAN FREEWAYS

$StdDevTTI = 0.71 \times (MeanTTI - 1.0)^{0.56}$

3.0   DATA AVAILABLE

Given that many of the model enhancements described in Chapter 2.0 requires borrowing parameters from other regions, a detailed model calibration effort is necessary to ensure that the model improvements closely match local conditions. The base-year for model calibration is 2012. This section describes data available for model calibration and validation.

3.1 | DISAGGREGATE DATA

SANDAG conducted a household survey in 2006 consisting of approximately 3,500 households. This data has been coded into CT-RAMP format (tours and trips with consistent activity, mode, and time-of-day representation) and was used for CT-RAMP model estimation for the San Diego region. SANDAG conducted a system-wide transit on-board survey in 2009, yielding approximately 20,000 origin-destination records. This data was used for mode choice calibration targets and transit assignment path-finding adjustments and validation.

3.2 | TRAFFIC COUNTS

SANDAG maintains an inventory of traffic counts assembled from several sources:

- The Caltrans PeMS system also provides 5-minute and hourly freeway counts and speeds for approximately 1400 locations in the SANDAG region.

- Approximately 160 other Caltrans counts on freeways and state routes.

- A number of counts on arterials assembled from local jurisdictions.

All of the counts are available by time-of-day period. Though, coverage is relatively sparse below the level of major arterial.

3.3 | TOLL DATA

SANDAG operates two toll facilities in San Diego County, see Figure 4; dynamically priced High-Occupancy Toll (HOT) lanes on I-15, and the SR-125 toll road. SANDAG operates an integrated corridor management system (ICMS) for the I-15 corridor, with real-time demand and pricing data collected continuously. Toll pricing and demand data was obtained from SANDAG Department of Operations staff and analyzed for this project.
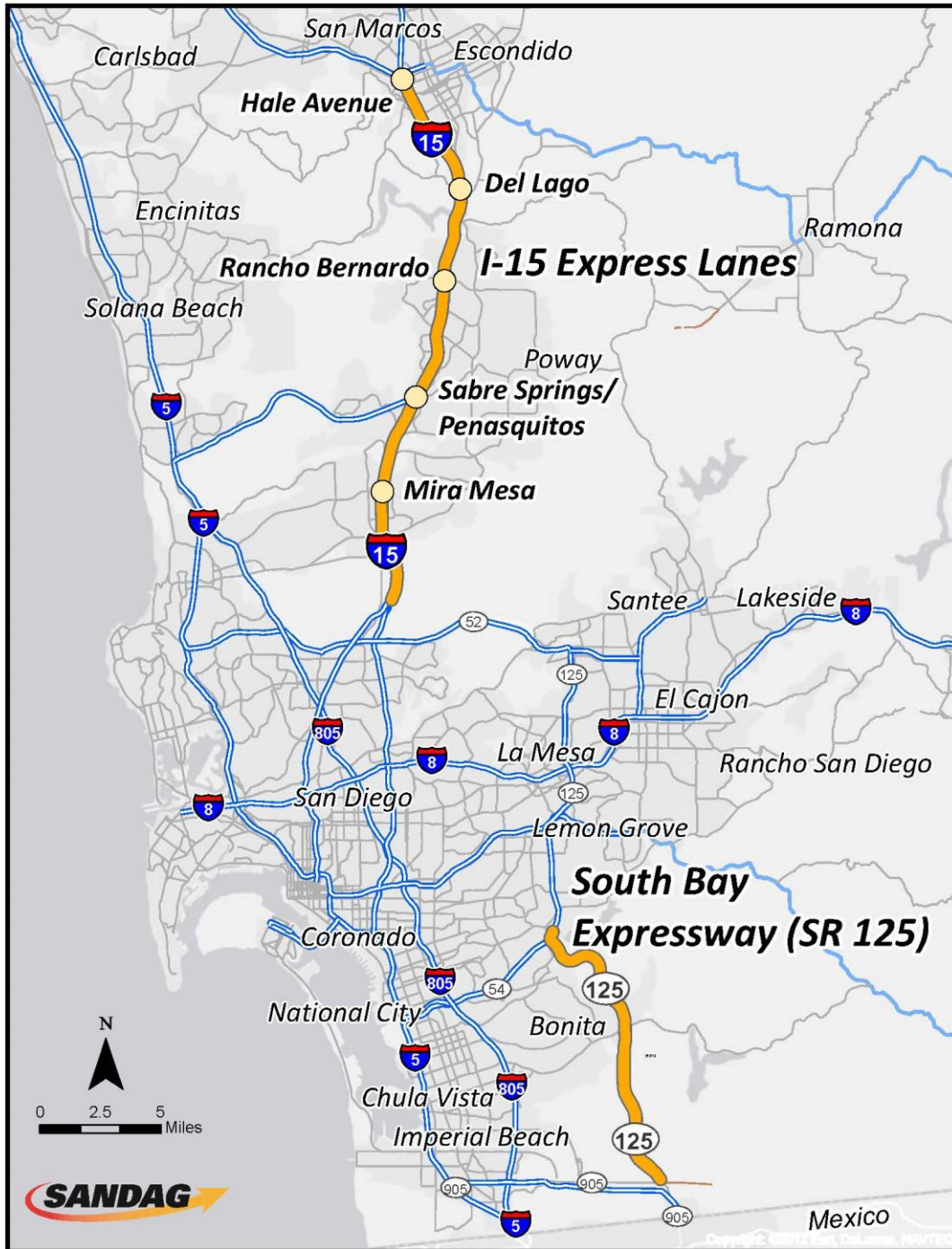
FIGURE 4. TOLL FACILITIES IN SAN DIEGO COUNTY (SOURCE: FASTRAK)

SR125 TOLL ROAD

Figure 5 presents entry and exit toll gates on the SR125 toll road (South Bay Expressway).
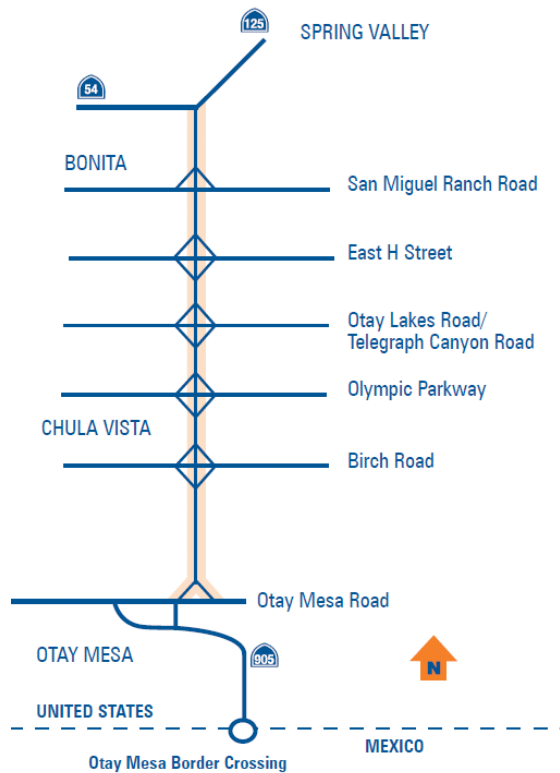
FIGURE 5. ENTRY AND EXIT POINTS ON SR125 TOLL FACILITY

The northbound (NB) direction of the toll road starts at Otay Mainline Toll Plaza and ends at SR 54 gate. The southbound (SB) direction of the toll road starts at SR54 gate and ends at Otay Mainline Toll Plaza. Note that southbound entries and northbound exits on San Miguel Ranch Road gate do not exist.

Table 2 and

Table 3 show consecutive entry and exit pairs for NB and SB direction respectively. The pairs are listed in the order of travel direction. An entry and exit pair in the table represents a road segment on the facility.

TABLE 2. NB ENTRY AND EXIT GATE PAIRS ON SR125

Entry	Exit
Otay Mainline Toll Plaza	Birch Road
Birch Road	Olympic Parkway
Olympic Parkway	Otay Lakes Road
Otay Lakes Road	East H Street

| East H Street | San Miguel Ranch Road |
| San Miguel Ranch Road | SR54 |

TABLE 3. SB ENTRY AND EXIT GATE PAIRS ON SR125

Entry	Exit
SR54	San Miguel Ranch Road
San Miguel Ranch Road	East H Street
East H Street	Otay Lakes Road
Otay Lakes Road	Olympic Parkway
Olympic Parkway	Birch Road
Birch Road	Otay Mainline Toll Plaza

Toll value data were extracted from the toll schedule in "TollSchedule0612.pdf". The data provide toll dollars for every possible entry (origin) and exit (destination) pair by direction (NB or SB), by axle type (2-axle or 3 or more axle), and by payment type (Fast Trak [3] or Cash/Credit). The current SANDAG ABM system does not distinguish demand by payment type, therefore SANDAG calculated weighted tolls based on payment type shares. Both original and weighted tolls are presented in Table 4 and Table 5. The tolls indicated are for 2-axle vehicles per one-way trip. Vehicles with three or more axles pay two times the 2-axle toll rate.

TABLE 4. NB TOLLS (CENTS) ON SR125 TOLL FACILITY

Entry Plaza	Exit Plaza	FastTrak Cost	Cash/Credit Cost	Weighted Cost
Otay Mainline Toll Plaza	Birch Road	195	350	222
Otay Mainline Toll Plaza	Olympic Parkway	195	350	222
Otay Mainline Toll Plaza	Otay Lakes Road	195	350	222
Otay Mainline Toll Plaza	East H Street	200	350	226
Otay Mainline Toll Plaza	SR54	275	350	279
Birch Road	Olympic Parkway	50	250	95
Birch Road	Otay Lakes Road	50	250	95
Birch Road	East H Street	50	250	95
Birch Road	SR54	170	250	221

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[3] FasTrak is an electronic toll collection system. A small electronic device called a transponder is placed on the inside of your vehicle's windshield. The transponder works together with electronic readers installed along the South Bay Expressway. (Source: http://sbxthe125.com/how-to-use-sbx/about-sbx)

Olympic Parkway	Otay Lakes Road	50	250	95
Olympic Parkway	East H Street	50	250	95
Olympic Parkway	SR54	170	250	221
Otay Lakes Road	East H Street	50	250	95
Otay Lakes Road	SR54	170	250	221
East H Street	SR54	170	250	221
San Miguel Ranch Road	SR54	155	200	159

TABLE 5. SB TOLLS (CENTS) ON SR125 TOLL FACILITY

Entry Plaza	Exit Plaza	FastTrak Cost	Cash/Credit Cost	Weighted Cost
SR54	San Miguel Ranch Road	155	200	159
SR54	East H Street	170	250	221
SR54	Otay Lakes Road	170	250	221
SR54	Olympic Parkway	170	250	221
SR54	Birch Road	170	250	221
SR54	Otay Mainline Toll Plaza	275	350	279
East H Street	Otay Lakes Road	50	250	95
East H Street	Olympic Parkway	50	250	95
East H Street	Birch Road	50	250	95
East H Street	Otay Mainline Toll Plaza	200	350	226
Otay Lakes Road	Olympic Parkway	50	250	95
Otay Lakes Road	Birch Road	50	250	95
Otay Lakes Road	Otay Mainline Toll Plaza	195	350	222
Olympic Parkway	Birch Road	50	250	95
Olympic Parkway	Otay Mainline Toll Plaza	195	350	222
Birch Road	Otay Mainline Toll Plaza	195	350	222

Note that the entry and exit points in the two tables are arranged in the order encountered in the travel direction.

The toll demand data is a summary of average trips by axle and payment type and average travel time between every interchange on SR-125 by 15-minute interval in October 2012. The data is summarized by five SANDAG assignment periods for both toll value and toll demand between consecutive entry and exit points. First, the data is aggregated to five time periods by axle and payment type for each entry and exit points. Then the aggregated data is summarized at a link-level (consecutive entry and exit points) by direction for the five model time periods. Table 6 and Table 7 present NB and SB direction observed toll demand on the SR 125 facility.

TABLE 6. NB OBSERVED TOLL DEMAND ON SR 125 BY TIME PERIOD

Entry Plaza	Exit Plaza	EA	AM	MD	PM	EV	Total

Otay Mainline Toll Plaza	Birch Road	33	229	914	1,113	448	**2,737**
Birch Road	Olympic Parkway	63	635	1,039	1,133	491	**3,363**
Olympic Parkway	Otay Lakes Road	162	1,537	1,508	1,331	648	**5,186**
Otay Lakes Road	East H Street	269	2,537	2,325	1,685	885	**7,701**
East H Street	San Miguel Ranch Road	351	3,224	2,795	1,810	935	**9,115**
San Miguel Ranch Road	SR54	424	3,755	3,111	1,979	1,031	**10,300**

TABLE 7. SB OBSERVED TOLL DEMAND ON SR 125 BY TIME PERIOD

Entry Plaza	Exit Plaza	EA	AM	MD	PM	EV	Total
SR54	San Miguel Ranch Road	150	1,292	2,497	3,095	1,579	**8,614**
San Miguel Ranch Road	East H Street	142	1,212	2,262	2,739	1,368	**7,722**
East H Street	Otay Lakes Road	148	1,216	1,947	2,132	1,036	**6,479**
Otay Lakes Road	Olympic Parkway	142	1,106	1,387	1,277	624	**4,536**
Olympic Parkway	Birch Road	154	1,154	1,074	695	327	**3,404**
Birch Road	Otay Mainline Toll Plaza	164	1,073	917	357	196	**2,707**

The gate pairs are listed in the order encountered in travel direction. Generally, total toll demand on a link (consecutive entry and exit pair) increases as the link approaches the northern end of the corridor which provides access to the facilities and activity locations in San Diego County, as demand builds from more entry points.
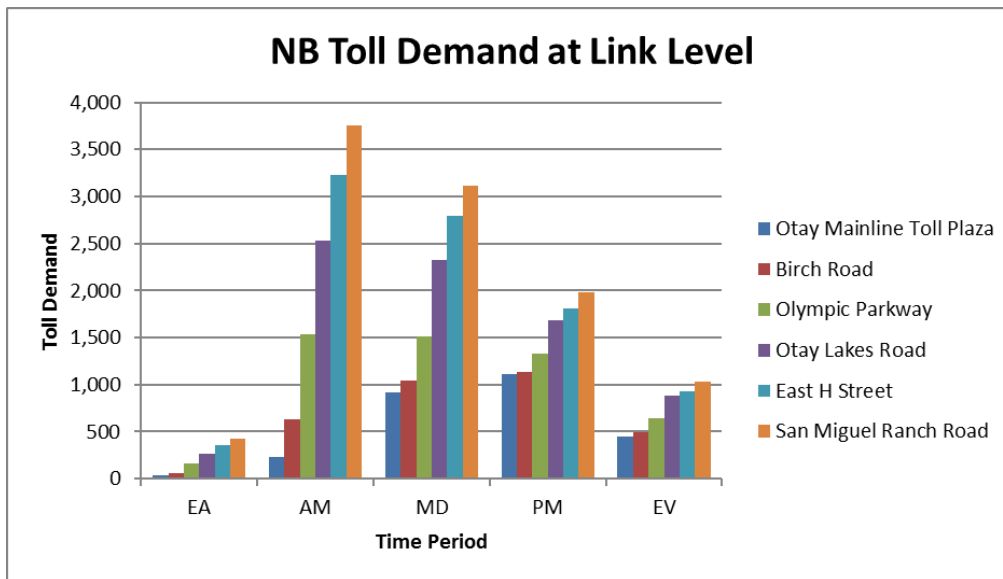
FIGURE 6. NB OBSERVED TOLL DEMAND ON SR 125
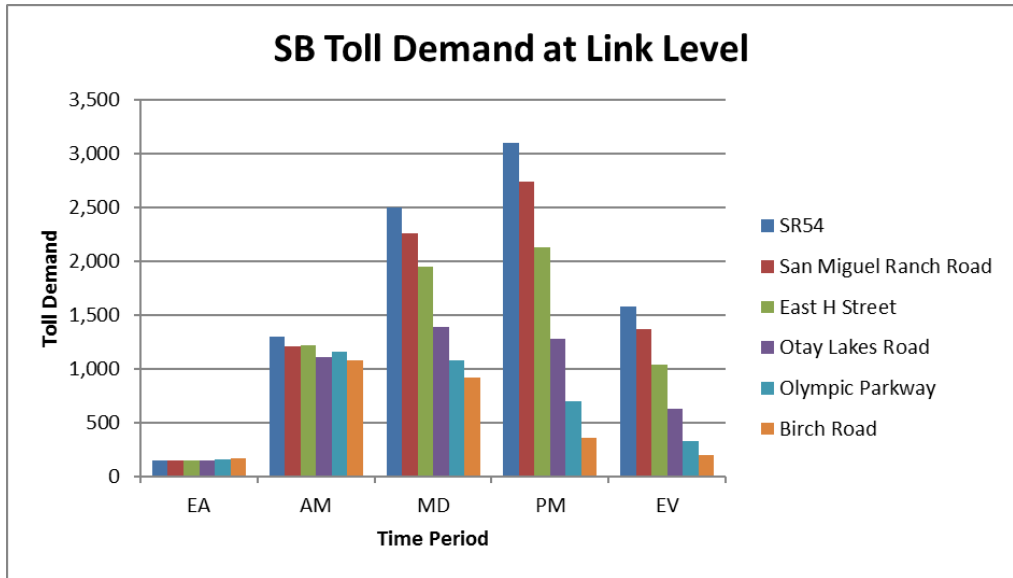
FIGURE 7. SB OBSERVED TOLL DEMAND ON SR 125

Figure 6 and Figure 7 show the demand by time of day for the northbound and southbound directions respectively. The summaries show that the AM period is the peak period in NB direction and the PM period is the peak period in SB direction. Irrespective of the direction, MD period also sees a lot of demand, primarily due to longer period duration compared to the peak periods. Early morning (EA) observes the lowest demand on the facility as travel is always low during this time period. Figure 6 and show the demand by time of day for the northbound and southbound directions respectively. The summaries show that the AM period is the peak period in NB direction and the PM period is the peak period in SB direction. Irrespective of the direction, MD period also sees a lot of demand, primarily due to longer period duration compared to the peak periods. Early morning (EA) observes the lowest demand on the facility as travel is always low during this time period. Figure 6 shows the demand by time of day for the northbound and southbound directions respectively. The summaries show that the AM period is the peak period in NB direction and the PM period is the peak period in SB direction. Irrespective of the direction, MD period also sees a lot of demand, primarily due to longer period duration compared to the peak periods. Early morning (EA) observes the lowest demand on the facility as travel is always low during this time period.

The process of calculating daily demand at link level is automated in an excel spreadsheet ("SR125Summary_ObservedData.xlsx") and is made available to SANDAG.

I15 MANAGED LANE

Figure 8 shows the managed lane corridor with entry and exit points.
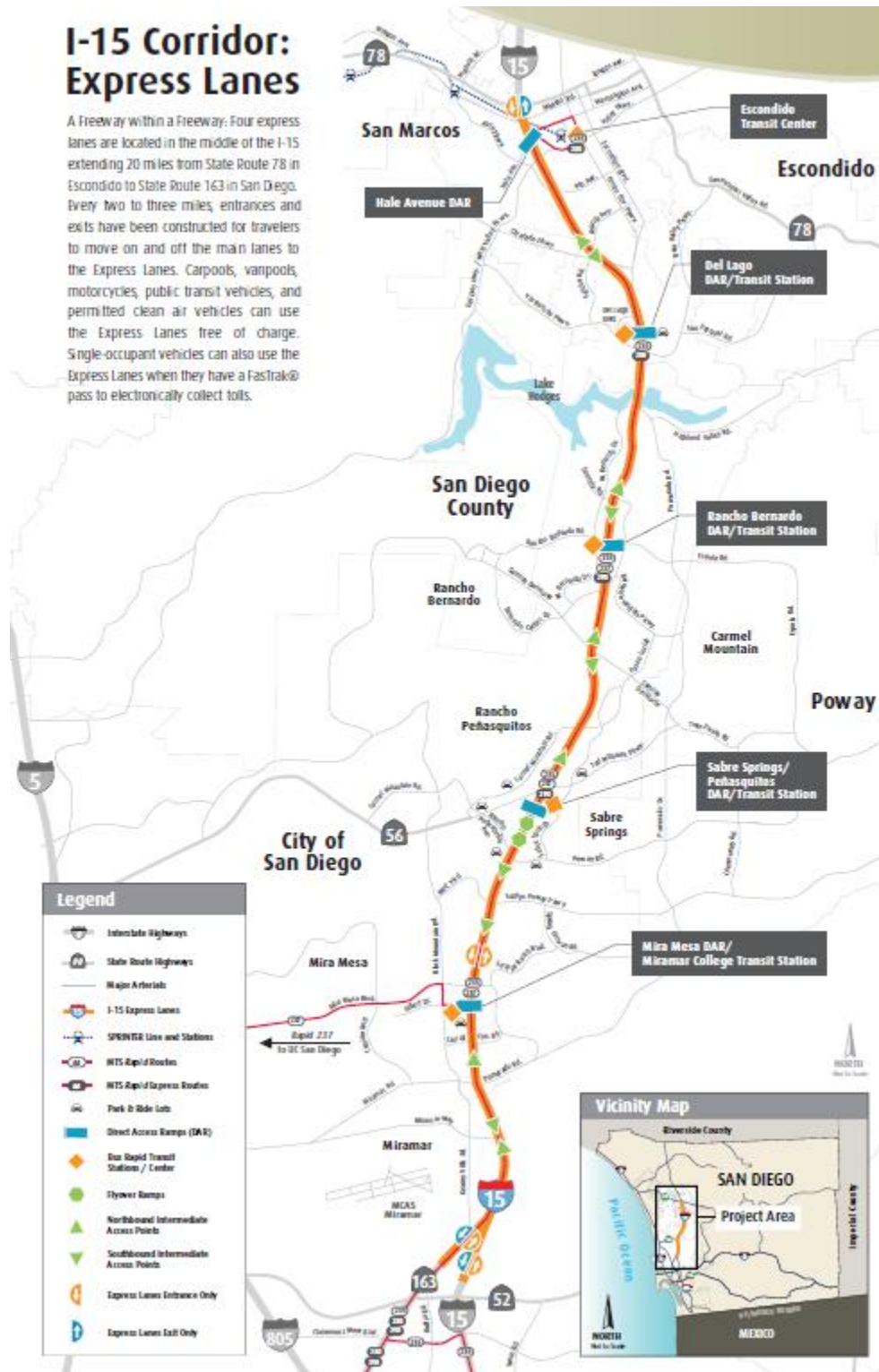
FIGURE 8. I15 CORRIDOR – EXPRESS LANE (SOURCE: FASTREK)

A list of entry and exit pairs on the facility are presented in Table 8 and Table 9. The pairs are listed in the order of travel direction. An entry and exit pair represents a road segment on the facility.

TABLE 8. NB ENTRY AND EXIT POINTS ON I15 EXPRESS LANES

Entry	Exit
I-15 Access	Miramar Rd NB
SR 163 Access	Miramar Rd NB
Ammo Rd NB	Miramar Rd NB
Miramar Rd NB	SR 56-1 NB Exit
Mira Mesa Bl NB	SR 56-1 NB Exit
Sabre Springs Transit	SR 56-2 NB
SR 56-2 NB	Camino Del Norte NB
Camino Del Norte NB	Rancho Bernardo Transit
Rancho Bernardo Transit	Duenda Rd NB
Duenda Rd NB	Del Lago NB Exit
Del Lago NB Entry	Center City Pkwy NB
Center City Pkwy NB	Hale Ave NB Exit
Center City Pkwy NB	SR 78

TABLE 9. SB ENTRY AND EXIT POINTS ON I15 EXPRESS LANES

Entry	Exit
SR 78	9th Ave SB
Hale Ave SB Entry	9th Ave SB
9th Ave SB	Del Lago SB Exit
Del Lago SB Entry	Duenda Rd SB
Duenda Rd SB	Rancho Bernardo Transit
Rancho Bernardo Transit	Camino Del Norte SB
Camino Del Norte SB	SR 56 SB
Camino Del Norte SB	Sabre Springs Transit
Sabre Springs Transit	Poway Rd SB
SR 56 SB	Poway Rd SB
Poway Rd SB	Mercy Rd-1 SB
Mercy Rd-1 SB	Miramar Rd SB
Mercy Rd-2 SB	Miramar Rd SB
Miramar Rd SB	SR 163 Access

The data is for each potential entry-exit pair, by direction, and in 15 minute increments according to time vehicle enters the facility. The data is for the entire month of October 2012 (excluding weekends) and provides following information for an entry-exit pair:

- Total trips
- Total toll charged (cents)
- Total travel time (seconds)
- Average toll charged (cents)
- Average travel time (seconds)

The data is for single-occupancy-vehicle (SOV) toll and included violators as well. However, Non-AVI (HOV and violators) data were also provided. As the I15 managed lane facility allows HOV trips to travel for free, they are not available in the toll transaction data. Violators cannot be modeled and are removed from the dataset to make a fair comparison with the estimated data. The summarized data included only SOV toll demand. The average toll charged for every possible entry-exit pair by time period and by direction is provided in Appendix E.

The monthly demand data is converted to daily demand by dividing it with number of weekdays (23 days) in the month. Table 10 and Table 11 present NB and SB direction observed toll demand at link level on the I15 facility. The corresponding demand plots by time period are shown in Figure 9 and Figure 10.

TABLE 10. NB OBSERVED TOLL DEMAND ON I15 MANAGED LANE FACILITY

Entry Plaza	Exit Plaza	EA	AM	MD	PM	EV	Total
I-15 Access	Miramar Rd NB	11	145	309	602	60	1,128
SR 163 Access	Miramar Rd NB	14	186	478	1,101	108	1,887
Ammo Rd NB	Miramar Rd NB	17	235	644	1,519	151	2,567
Miramar Rd NB	SR 56-1 NB Exit	17	231	673	1,622	159	2,703
Mira Mesa Bl NB	SR 56-1 NB Exit	18	243	736	1,807	175	2,978
Sabre Springs Transit	SR 56-2 NB	17	225	655	1,447	145	2,489
SR 56-2 NB	Camino Del Norte NB	16	210	684	1,320	154	2,385
Camino Del Norte NB	Rancho Bernardo Transit	17	221	709	1,401	158	2,505
Rancho Bernardo Transit	Duenda Rd NB	15	165	688	1,448	157	2,473
Duenda Rd NB	Del Lago NB Exit	15	156	669	1,385	150	2,377
Del Lago NB Entry	Center City Pkwy NB	16	182	658	1,257	142	2,255
Center City Pkwy NB	Hale Ave NB Exit	12	115	465	856	101	1,549
Center City Pkwy NB	SR 78	8	70	397	751	92	1,317

TABLE 11. SB OBSERVED TOLL DEMAND ON I15 MANAGED LANE FACILITY

Entry Plaza	Exit Plaza	EA	AM	MD	PM	EV	Total
SR 78	9th Ave SB	139	1,109	367	138	30	1,783
Hale Ave SB Entry	9th Ave SB	145	1,239	427	182	33	2,026
9th Ave SB	Del Lago SB Exit	164	1,491	528	233	42	2,458
Del Lago SB Entry	Duenda Rd SB	183	1,714	573	230	41	2,741
Duenda Rd SB	Rancho Bernardo Transit	191	1,779	606	252	43	2,871
Rancho Bernardo Transit	Camino Del Norte SB	189	1,792	620	315	48	2,964
Camino Del Norte SB	SR 56 SB	185	1,945	639	323	47	3,139
Sabre Springs Transit	SR 56 SB	186	2,028	650	333	47	3,244
SR 56 SB	Poway Rd SB	187	2,350	707	361	49	3,654
Poway Rd SB	Mercy Rd-1 SB	194	2,292	787	413	57	3,743
Mercy Rd-1 SB	Miramar Rd SB	165	1,798	674	370	48	3,056
Mercy Rd-2 SB	Miramar Rd SB	167	1,842	700	387	50	3,146
Miramar Rd SB	SR 163 Access	155	1,623	662	372	49	2,862
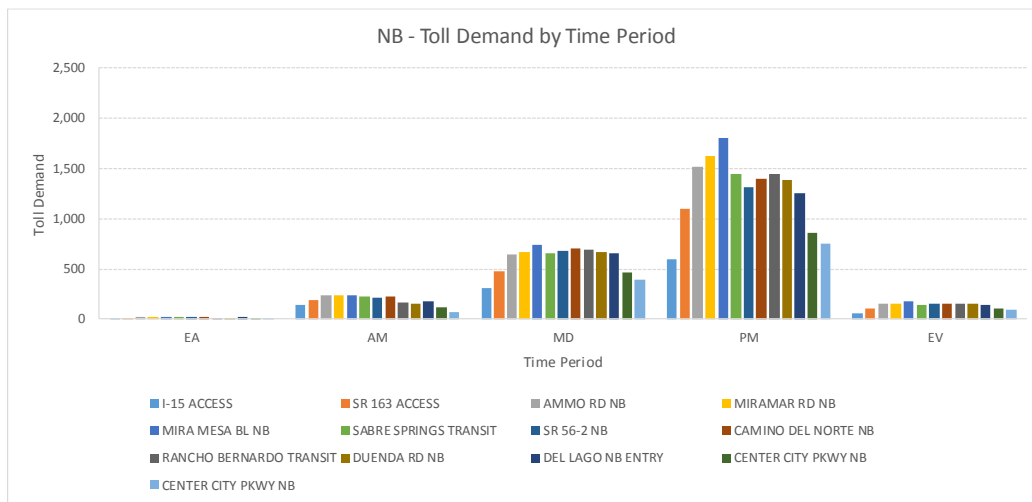
FIGURE 9. NB OBSERVED DEMAND ON I15
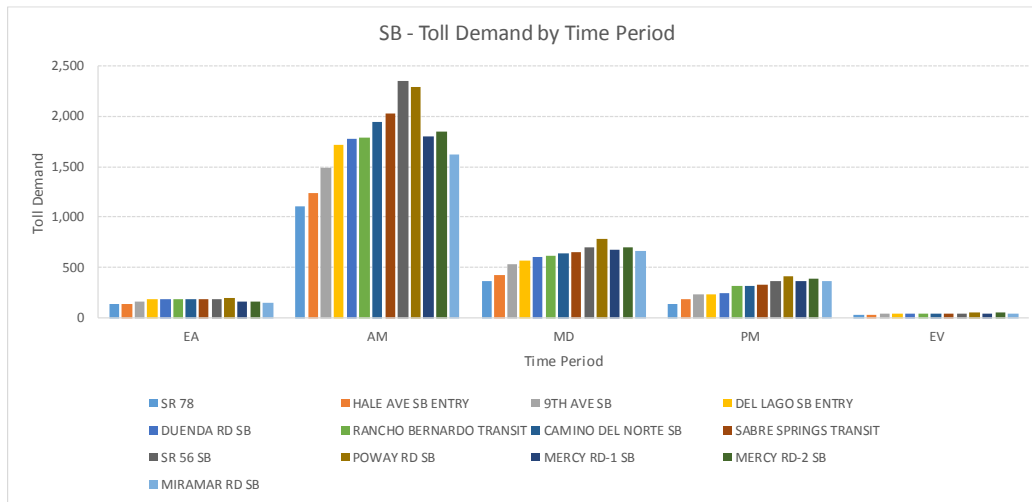
FIGURE 10. SB OBSERVED DEMAND ON I15

The summaries show that the PM period is the peak period in NB direction and the AM period is the peak period in SB direction. In the NB direction, the toll demand peaks at the segment between 'Mira Mesa Bl NB' and 'SR 56-1 NB Exit' gates, which is also true by time periods. The SB direction toll demand peaks at the segment between 'Poway Rd SB' and 'Mercy Rd-1 SB'. Even though the MD period has longer duration, the demand is not that high. During the period, the I15 general purpose lanes are likely be functioning uncongested, thus not significant benefit for vehicles to switch to the toll lanes. In either direction, the toll demand is very small during the off-peak periods, EA and EV.

The process of calculating daily demand at link level is automated in an excel spreadsheet ("I15Summary_ObservedData.xlsx") and is made available to SANDAG.

3.4 | TRAVEL TIME DATA

SANDAG provided INRIX travel time and speed data for the entire month of October in 2012. The INRIX data are in 1-minute increments and available for freeways, major and minor arterials, collectors and some ramps. The dataset includes a good coverage in the SANDAG region.

SANDAG provided a correspondence between the model network segments and the INRIX TMC segments. The correspondence included one record for each model link-to-INRIX TMC segment. Note that some model links may correspond to multiple TMC segments; in such cases the proportion of the TMC feature covered by the corresponding model network feature was also provided. Records corresponding to a link with excessive number of TMC segments assigned are flagged as they may not represent true correspondence.

While preparing INRIX data for the project, the records that were flagged in the correspondence file were removed. Then, a TMC segment was assigned to one model link by finding the record with the highest TMC proportion. The characteristics of that model link were attached to the TMC segment. The resulting dataset includes about 660 miles centerline of freeways and 1,400 miles total centerlines.

SPEED DISTRIBUTION

The analysis was restricted to weekdays and weekend's data points were eliminated from the dataset. During the initial analysis, the distribution of speeds (miles per hour) in 24-hour period were studied. Speed profiles of freeways and ramps showed congestion during AM and PM peak periods. Other facilities had relatively high speed variation throughout the day (AM, MD, and PM) with no recognizable pattern during a period. Figure 11 shows the speed profile of Interstate 5 in Del Mar Heights, San Diego, CA. The Y-axis represents speed (in mph) and the X-axis represents time of day (in hours) starting from midnight. The five time periods (EA, AM, MD, PM, EV) used in the model are also identified on the X-axis.

As expected, the PM peak period experienced high congestion and other time periods indicate close to free-flow conditions on the segment. Due to the directional nature of the facility, congestion was seen only in the PM peak period. It is also clear that variability tends to increase with congestion, and the highest levels of variability occur in the peak of the peak periods.

Speed profiles of individual days indicate that the unusual drops in speed in other periods occurred only on a few particular days and could have been the result of unexpected events such as accidents, also known as 'non-recurring congestion'. Non-recurring congestion due to occasional accidents does not represent typical weekday conditions and is not represented in the travel demand model. Therefore, such data points are outliers and must be removed from the analysis. The outlier detection method used in this research is described in the next section.
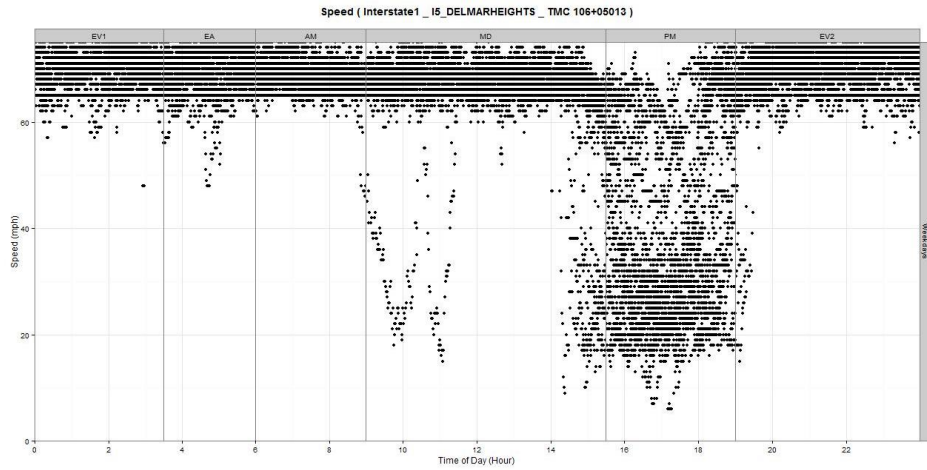
1(a) − Speed Profile with Outliers
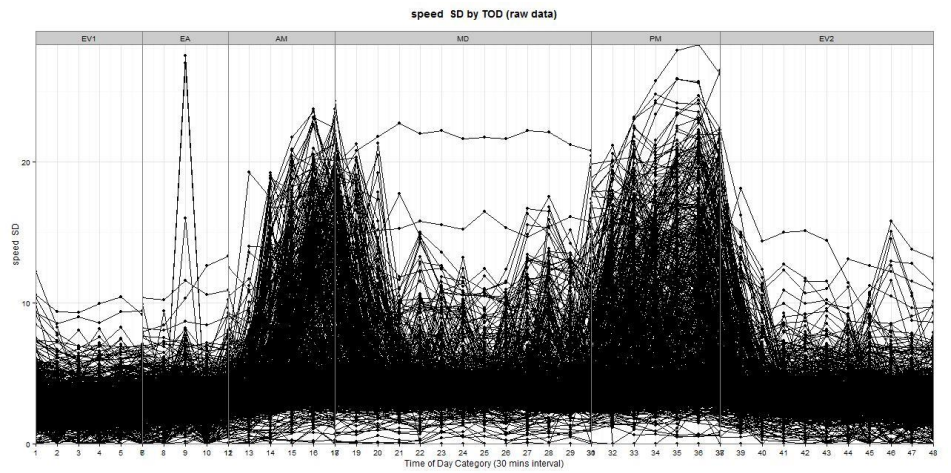
2(a) − Speed Variability with Outliers
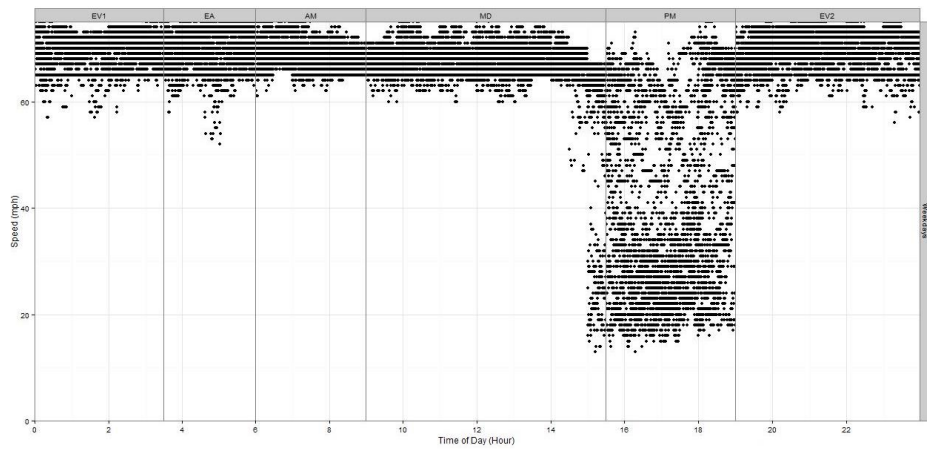
1(b) − Speed Profile without Outliers
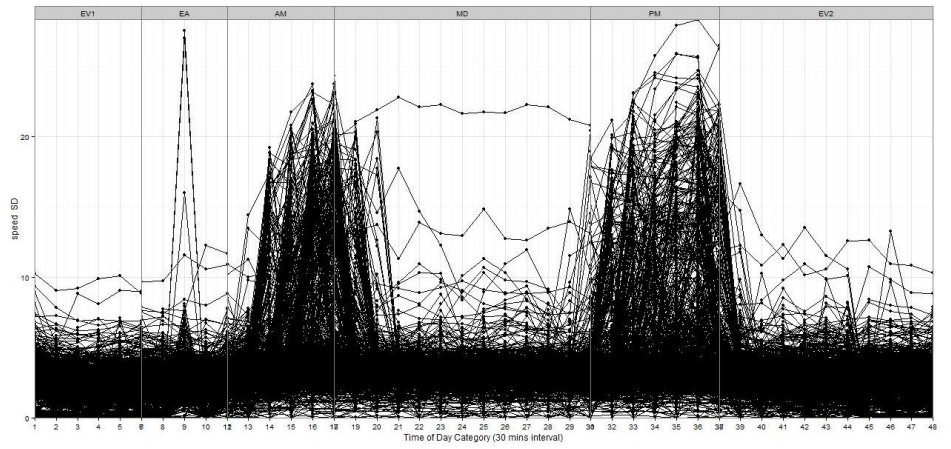
2(b) − Speed Variability without Outliers

FIGURE 11. 1. SPEED PROFILES OF INTERSTATE (I5) – DEL MAR HEIGHTS. 2. VARIABILITY IN SPEED ON FREEWAYS IN SAN DIEGO COUNTY

OUTLIER DETECTION

A typical approach to outlier detection is to first determine upper and lower limits in the nominal range of data variation, and then identify any point falling outside this range as an outlier. The analysis in this research used an adjusted box plot method to compute upper and lower limits of the nominal data range. The adjusted box plot method is an extension of a standard box plot. It uses upper and lower quartiles, along with a robust skewness estimator called the "medcouple" to form a nominal data range. The data points falling outside the following nominal data range are considered outliers:

$$\{Q25 - c*IQR, Q75 + c*IQR\}$$

Where: Q25 is the 25th percentile; Q75 is the 75th percentile; IQR is the interquartile range; and c is a threshold parameter.

In a standard boxplot the threshold parameter c is set to 1.5. The adjusted box plot method modifies the threshold parameter by an amount that depends on the asymmetry of the distribution, modifying the upper threshold and the lower threshold differently.

First, daily data points of a segment were divided into 96 time intervals of 15 minutes each. Then for each time interval, an adjusted box plot was created and nominal data range was calculated. The data points of the interval that fell outside the range were detected and identified as outliers. Overall, the approach identified about 8% of the data points in the dataset as outliers. Figure 11 2 (b) shows speed profile of an interstate (I5) in Del Mar Heights, San Diego, CA after removing outliers. From the comparison of the Figure 11 1 (a) and Figure 11 1 (b), it is evident that the data points with unusual speeds in the MD period were caught and removed by the outlier detection process.

SPEED VARIABILITY

Speed variability is measured by calculating the standard deviation of speeds within each time interval. In this analysis, the speed variability was calculated for every 15 minutes throughout 24-hours by taking the standard deviation across all weekdays within October 2012. The variabilities were calculated for the two datasets, with and without outliers. For each dataset, the speed variabilities of segments during the 24-hour period were plotted by facility type. The plots of the two datasets were compared to identify the effects of the outlier detection process.

Figure 11 2(a) and Figure 11 2(b) show speed variabilities of all freeway segments in the dataset with outliers and the dataset without outliers respectively. In the figures, a line represents a freeway segment. As expected, in general, the variability was lower without the outliers. Surprisingly, the period between 4:00 am-4:30 am showed a high variability in speeds. The unexpected variability was not just on freeway segments but appears to be consistent across facility types. Further investigation revealed that between 4:14 am and 4:15 am, speeds suddenly jump from an unreasonably low value (around 10 MPH) to a more reasonable speed (65 MPH). Due to presence of sufficient low and high speed observations during the time interval, the outlier detection process considers all observations within the threshold of valid points. After a discussion with SANDAG, the speeds between 4:15 am – 4:30 am were compared against reference speeds and if the difference of the two was greater than 5 mph, the data point was considered an outlier, thus removed. Discussions with INRIX indicated that these low speeds may have been the result of insufficient observations during the time period or data processing issues prior to receipt of data by SANDAG.

Further, to understand spatial patterns of unreliable segments, speed variabilities were plotted on a map of San Diego county. Freeway segments showed more unreliable (high variability) segments while arterial segments tend to be more reliable segment. Figure 12 shows speed variabilities on freeway segments during 5:30 pm – 6:00 pm (PM) time period.

Speed Standard Deviation (5:30pm-6:00pm)
- 0.000000 - 3.000000
- 3.000001 - 7.000000
- 7.000001 - 25.692287
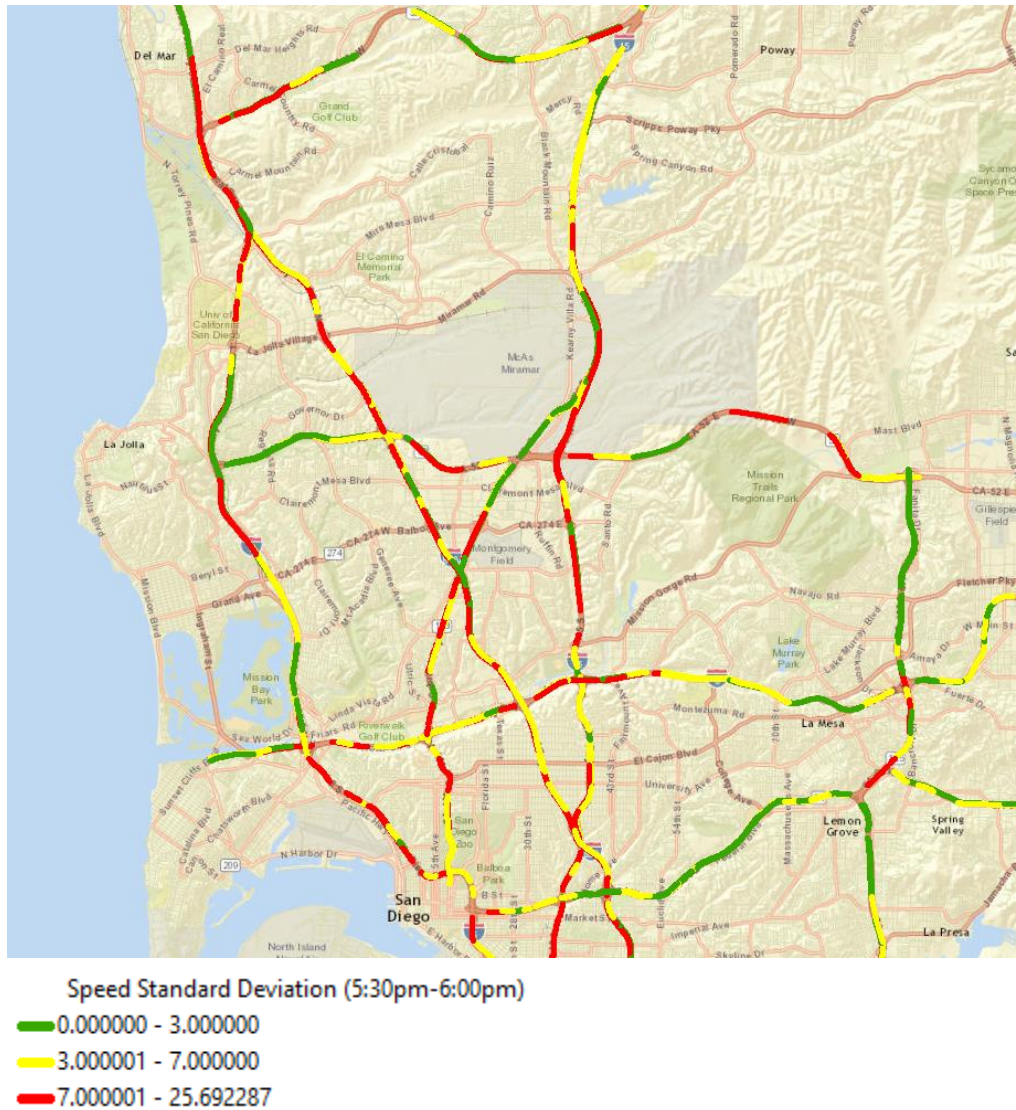
FIGURE 12. MAP OF SPEED VARIABILITY ON FREEWAY SEGMENTS IN SAN DIEGO COUNTY

The map shows a pattern of more unreliable speeds (higher standard deviation) on freeway segments closer to interchanges. The pattern appears intuitive as weaving patterns due to traffic entering and leaving a facility may cause traffic to slow down, leading to greater speed variability. The travel time reliability data was used to estimate equations that predict speed variability, as described in Section 4.0.

4.0 TRAVEL TIME RELIABILITY

4.1 | MODEL ESTIMATION

The SHRP L03 presents equations to estimate travel time reliability (see Chapter 2.0). This project re-estimated those equations locally using the INRIX travel time data for the San Diego region and calculated specific factors for each facility type in the SANDAG transportation network.

Separate regression models are developed for each facility type. Four facility classes, Table 12, are constructed based on the initial functional classification (IFC) in the roadway database.

TABLE 12. FACILITY CLASSES IN ESTIMATION DATASET

Facility Class	IFC	Description
Freeway	1	Freeways
Arterial	2,3	Major arterials, prime arterials
Ramp	8,9	Local ramps, freeway ramps
Other	4,5,6,7	Collectors and local streets

80% of the data is used in estimating regression models and the remaining 20% is retained for validating estimated models. The two datasets are created using random sampling by facility type. Table 13 presents count segments in by facility class in the two datasets.

TABLE 13. DATA SIZE BY FACILITY CLASS

Facility Class	All Data	Estimation Data (80%)	Validation Data (20%)
Freeway	1,020	816	204
Arterial	1,482	1,185	297
Ramp	130	104	26
Other	355	284	71

Freeway and arterial facility classes have sufficient segments in the estimation dataset, however, ramp and other facility classes have low segment counts. Due to insufficient data in ramp and other facility classes, regression models were developed only for freeways and arterials. During implementation, ramp and other facility classes were applied with arterial estimates.

REGRESSION MODELS

A general form of the regression models developed during the project is presented in Equation 6.

EQUATION 6. FORM OF REGRESSION MODELS

$$\frac{\sigma_{time\ per\ mile}}{\mu_{travel\ time\ per\ mile}} = f(lanes, speed, intersection\ control, distance\ to\ interchange, time\ of\ day, \frac{volume}{capacity})$$

Travel time variability (standard deviation) per mile by mean travel time per mile is used as the independent variable.

A number of dependent variables were tried during regression model testing. The variables used in the final regression models are presented in Table 14. The table also shows corresponding facility classes that use the variable.

TABLE 14. VARIABLES USED IN FINAL REGRESSION MODELS

Variable	Facility Type
Number of Lanes	Arterial
Level-of-Service (LOS)	Freeway and Arterial
Posted Speed	Freeway and Arterial
Intersection Control Type	Arterial
Distance to Major Interchange	Freeway
Shift Variables	Freeway and Arterial

The variables that were tried but not used in the final models are presented in Table 15.

TABLE 15. VARIABLES NOT USED IN FINAL REGRESSION MODELS

Variable	Type	Description
I15	Binary	Presence of I15 facility
Intersection-approach capacity	Continuous	Intersection-approach capacity for arterials
Auxiliary lanes	Binary	Presence of auxiliary lanes
Left lanes	Continuous	Number of left lanes
Thru lanes	Continuous	Number of thru lanes
Right lanes	Continuous	Number of right lanes
V/C Ratio	Continuous	Volume-to-capacity ratio
G/C Ratio	Continuous	Green-to-cycle ratio at a signal for arterials
Lane increase	Continuous	Distance to lane increase
Lane drop	Continuous	Distance to lane drop
Ramp meter upstream	Binary	Presence of a ramp meter upstream
Ramp meter downstream	Binary	Presence of a ramp meter downstream

The dependent variables are calculated using information from highway database (hwy.dbd) and assignment results ('hwyload_[period].csv') produced in a model run. More details are presented below.

Number of Lanes

The link attribute is used in regression models for the arterial facility class. The highway line layer stores link lane information in three fields by time periods: ABLNO*, ABLNA*, and ABLNP*. Off-peak field (ABLNO*) is used to get lane counts during early AM (EA), mid-day (MD), and evening (EV) periods. AM peak (ABLNA) and PM peak (ABLNP) fields are used for AM and PM periods respectively.

Whether to choose lanes in link direction AB or BA is determined using TMC segment direction and link flows from highway assignment results. If a TMC segment is in positive direction ("P" or "+") and AB direction flow is non-zero then the AB field is picked, otherwise BA field is chosen. The interpretation of TMC codes is provided in Appendix A.

Number of lanes ('NumLanes') are categorized into five binary variables:

- One lane (1 if NumLanes=1, else 0)
- Two lane (1 if NumLanes=2, else 0)
- Three lane (1 if NumLanes=3, else 0)
- Four lane (1 if NumLanes=4, else 0)
- Five lane or more (1 if NumLanes>=5, else 0)

Level of service (LOS)

Level of service (LOS) represents traffic condition (congestion) and is determined based on volume to capacity ratio on the segment. The volume (flow) is obtained from assignment results. Capacity information is available in the highway database. Two types of link capacities exist in the database: mid-link capacity (ABCPO, ABCPA, ABCPP) and intersection approach capacity (ABCXO, ABCXA, ABCXP). The intersection approach capacity is available when one of the link ends is an intersection. Both sets of capacities are tried in regression model. Final models use mid-link capacities.

Link capacities from three time periods are converted to five model time periods using the same factors used in the ABM:

{EA, AM, MD, PM, EV} = {ABCPO*3/12, ABCPA *1, ABCPO *6.5/12, ABCPP *3.5/3, ABCPO*8/12}

Link direction (AB or BA) corresponding to a segment is determined using TMC segment direction.

After obtaining volume and capacity values the volume to capacity (v/c) ratio is calculated by taking their ratio. Based on the v/c ratio, six additive and multiplicative LOS variables are constructed to use in regression models:

LOSC+ = (V/C-0.69)* if (V/C>=0.70)

LOSD+ = (V/C-0.79)* if (V/C>=0.80)

LOSE+ = (V/C-0.89)* if (V/C>=0.90)

LOSF_LOW+ = (V/C-0.99)* if (V/C>=1.00)

LOSF_MED+ = (V/C-1.09)* if (V/C>=1.10)

LOSF_HIGH+ = (V/C-1.19)* if (V/C>=1.20)

Posted Speed

The field "ISPD" in the highway database contains posted speed on a link. Separate speed variables are constructed for freeway and arterial regression models.

Generally, posted speeds on freeways do not vary much. In San Diego county, the range of speed on freeways is 60 mph to 70 mph. A binary measure indicating if speed is 70 mph is used in freeway models.

Arterial segments see more variation in posted speeds, therefore, six binary variables are created:

- Speed less than 35 mph (ISPD35Less)
- Speed is 35 mph (ISPD35)
- Speed is 40 mph (ISPD40)
- Speed is 45 mph (ISPD45)
- Speed is 50 mph (ISPD50)
- Speed is higher than 50 mph (ISPD50More)

Intersection Control Type

Information of intersection control type is used only in arterial models. Highway database fields "ABCNT" and "BACNT" contain information of intersection control type at the TO end of a link. The fields are shown in Table 16.

TABLE 16. ABCNT/BACNT VALUES

Value	Label
0	No Control
1	Traffic Signal
2	All-Way Stop Sign
3	Two-Way Stop Sign
4	Ramp Meter
5	Ramp Meter with HOV lane meter
6	Light Rail Crossing
7	Toll Booth
9	Prevent Control

Whether to choose link direction AB or BA is determined using TMC segment direction and link flows from highway assignment results.

Based on the control type, four intersection control variables are constructed:

- No control (ICNT=0)
- Signal (ICNT=1)
- Stop (ICNT=2 or ICNT=3)
- Other (rail road etc.) (ICNT>3)

Distance to/from Major Interchange

As seen in Figure 12, freeways are more congested in proximity to freeway interchanges (major interchanges) suggesting potential weaving conflicts. To capture this effect in regression models, two measures of interchange proximity, upstream distance and downstream distance, are developed. Upstream distance is calculated as the distance PAST an interchanges and downstream distance is calculated as the distance TO an interchange. The distances are calculated from the mid-point of a link[4].

The freeway regression models use inverse of the distances. The use of inverse of distances makes it a little easier to understand their effect on travel time variability.

UpstreamDistance.Inverse = 1/UpstreamDistance

DownstreamDistance.Inverse = 1/DownstreamDistance

Shift variables

The travel time data is aggregated into 15-minute time of day bins. The variability plot, Figure 11, shows that travel time variability is highest during peak periods and decreases with distance away from peak periods. However, the shoulders of peak period show significant travel time variability. To capture this time-of-day effect within five broad periods, regression models use time-of-day variables that calculate distances away from peak periods. The distances are measured as number of 15-minute time bins. The variables are called as shift variables.

First, three time bins corresponding to maximum travel time (in AM and PM) and minimum travel time (in MD) are calculated over the entire dataset:

- Peak AM –time bin with maximum average travel time in the AM period
- Peak PM –time bin with maximum average travel time in the PM period

---

[4] A GISDK macro was written to calculate the interchange distances. The macro first identifies major interchanges in the highway node layer. To find major interchanges, first freeway ramps (query = 'IFC=8 AND position(NM,"HOV")=0') are identified. Then the highway nodes that are connected to the freeway ramps are selected. Now the nodes that are on the freeway links (IFC=1) are identified as Major Interchanges. Next, for every freeway link, from node and to node are obtained. Now the two nodes are used as starting point to traverse network in upstream (from node) and downstream (to node) direction to find an interchange. For each direction, a 'next link' is obtained by finding a 'link set' on the 'current node' and removing the current link. The node of the 'next link' that is not the 'current node' is identified as a 'next node'. When a 'next node' is obtained, it is checked if it is a major interchange. If yes, then the distance to this node is calculated as the distance in that direction (upstream or downstream). Otherwise, the process of finding 'next link' and 'next node' continues until one of the two happens:

- Node is a major interchange
- Maximum traversed links

If a major interchange is encountered, the length of all links traversed to the interchange is added up with half of the starting freeway link length to get the distance in that direction (upstream/downstream). If limit on maximum traversed link is reached, then a distance of 99 miles is assigned.

- Low MD – time bin with minimum average travel time in the MD period

Table 17 presents the time bins.

TABLE 17. PEAK AND LOW TRAVEL TIME BINS

	Time bin	Time of Day
Peak AM	32	8:00 AM
Peak PM	41	10:15 AM
Low MD	70	5:30 PM

Based on the three time bins, four shift variable categories are created, Table 18 and Figure 13:

TABLE 18. SHIFT VARIABLE CATEGORIES

Category	Start	End	Description
Before AM	00:00 AM	08:00 AM	Peak AM to start of day (counting backward)
After AM	08:00 AM	10:15 AM	Peak AM to low MD
Before PM	10:15 AM	05:30 PM	Peak PM to low MD (counting backward)
After PM	05:30 PM	00:00 AM	Peak PM to end of day

Shift variables are created based on step points within the categories. In each category, the first step point is always a peak time bin. Other step points are determined by looking at the average travel time (freeway) curve slope. Whenever the slope changed significantly, a new step point is set to create a new shift variable. Figure 13 and Table 19 below present the steps created in the four shift categories.
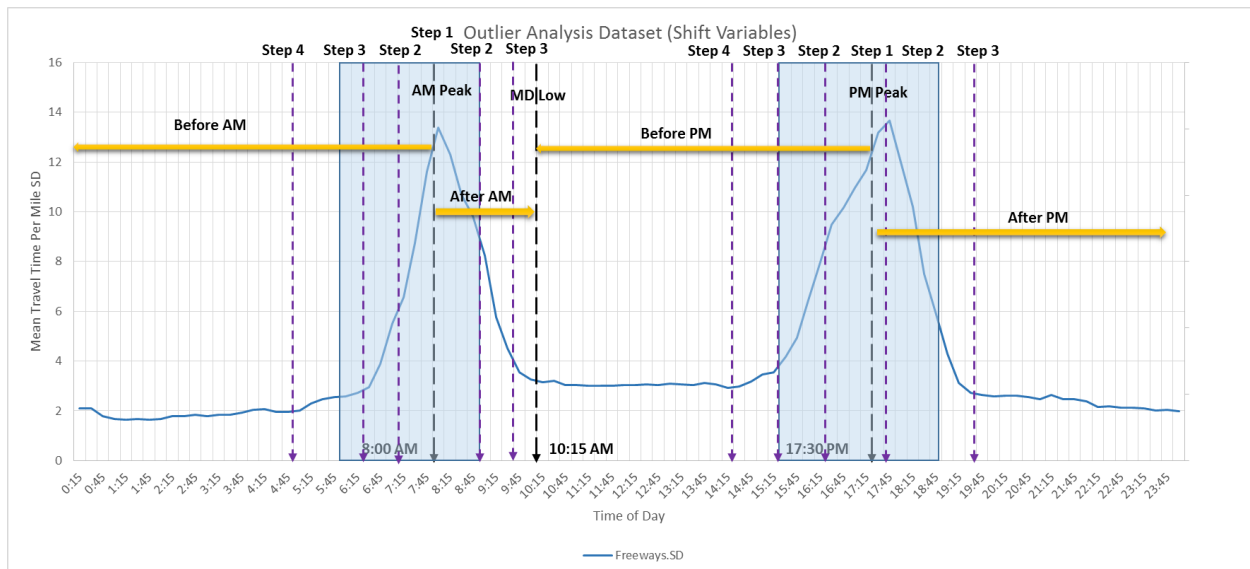
FIGURE 13. SHIFT VARIABLE BREAKS

TABLE 19. SHIFT VARIABLE BREAKS

Category	Start	End	Breaks	Time Bins
Before AM	00:00 AM	08:00 AM	5:00 AM, 6:30 AM, 7:15 AM, Peak AM	20, 26, 29, 32
After AM	08:00 AM	10:15 AM	Peak AM, 9:00 AM, 9:45 AM	32, 36, 39
Before PM	10:15 AM	05:30 PM	2:30 PM, 3:30 PM, 4:30 PM, Peak PM	58, 62, 66, 70
After PM	05:30 PM	00:00 AM	Peak PM, 5:45 PM, 7:45 PM	70, 71, 79

A shift variable is the distance calculated from the corresponding step point. The distance is calculated as the number of 15-minute time bins. Table 20 presents the variables and corresponding distance functions.

TABLE 20. SHIFT VARIABLE CALCULATION

Category	Breaks	Function
Before AM	Step 1	$(32 - tod)$ if $(tod<32)$, else 0
	Step 2	$(29 - tod)$ if $(tod<29)$, else 0
	Step 3	$(26 - tod)$ if $(tod<26)$, else 0
	Step 4	$(20 - tod)$ if $(tod<20)$, else 0
After AM	Step 1	$(tod-32)$ if $(tod>32)$, else 0
	Step 2	$(tod-36)$ if $(tod>36)$, else 0
	Step 3	$(tod-39)$ if $(tod>39)$, else 0
Before PM	Step 1	$(70 - tod)$ if $(tod<70)$, else 0
	Step 2	$(66 - tod)$ if $(tod<66)$, else 0
	Step 3	$(62 - tod)$ if $(tod<62)$, else 0
	Step 4	$(58 - tod)$ if $(tod<58)$, else 0
After PM	Step 1	$(tod-70)$ if $(tod>70)$, else 0
	Step 2	$(tod-71)$ if $(tod>71)$, else 0
	Step 3	$(tod-79)$ if $(tod>79)$, else 0

ESTIMATION RESULTS

A R script is written to construct variables and estimate regression models by facility class. The script ('RegressionAnalysys_Final.R') is provided to SANDAG.

Estimation results for freeways are shown in Table 21.

TABLE 21. ESTIMATION RESULTS - FREEWAYS

	Estimate	Std. Error	t value
(Intercept)	0.10780	0.00117	91.77
LOSC.Up	0.24290	0.01481	16.41
LOSD.Up	0.17050	0.03523	4.84
LOSE.Up	-0.22780	0.04616	-4.94
LOSF.Low.Up	-0.19830	0.04637	-4.28
LOSF.High.Up	1.02200	0.08611	11.87
ISPD70	0.01393	0.00103	13.51
BeforeAM.Step1	-0.01831	0.00076	-24.00
BeforeAM.Step2	0.00917	0.00156	5.90
BeforeAM.Step3	0.01065	0.00117	9.14
BeforeAM.Step4	-0.00192	0.00042	-4.56
AfterAM.Step1	-0.00820	0.00027	-30.53
BeforePM.Step1	-0.00667	0.00052	-12.74
BeforePM.Step2	-0.00285	0.00099	-2.88
BeforePM.Step3	0.00943	0.00058	16.12
AfterPM.Step1	-0.00771	0.00018	-41.96
AfterPM.Step3	0.00754	0.00026	28.60
MajorUpstream.Inverse	0.00110	0.00012	9.53
MajorDownstream.Inverse	0.00054	0.00009	5.97
Adjusted R-Squared		**0.181**	

All LOS variables except LOSD.Med.Up are estimated significant. As LOS variables are additive, the effect at a particular v/c ratio is additive of applicable LOS variables. For example, at v/c ratio of 0.8, the unreliability will include contributions from both LOSC.Up and LOSD.Up. As shown in Figure 14, the travel time unreliability (std. dev.) increases with higher v/c ratio. Variability for freeways flattens out at LOSF (v/c>1.0) with a sharp increase at a very high v/c ratio (LOSF.High.Up). Variability on arterials increases at a steady rate at LOS F.

Facility	Avg. Speed (mph)	Mean TT (secs)
Freeway	65	55
Arterial	45	80
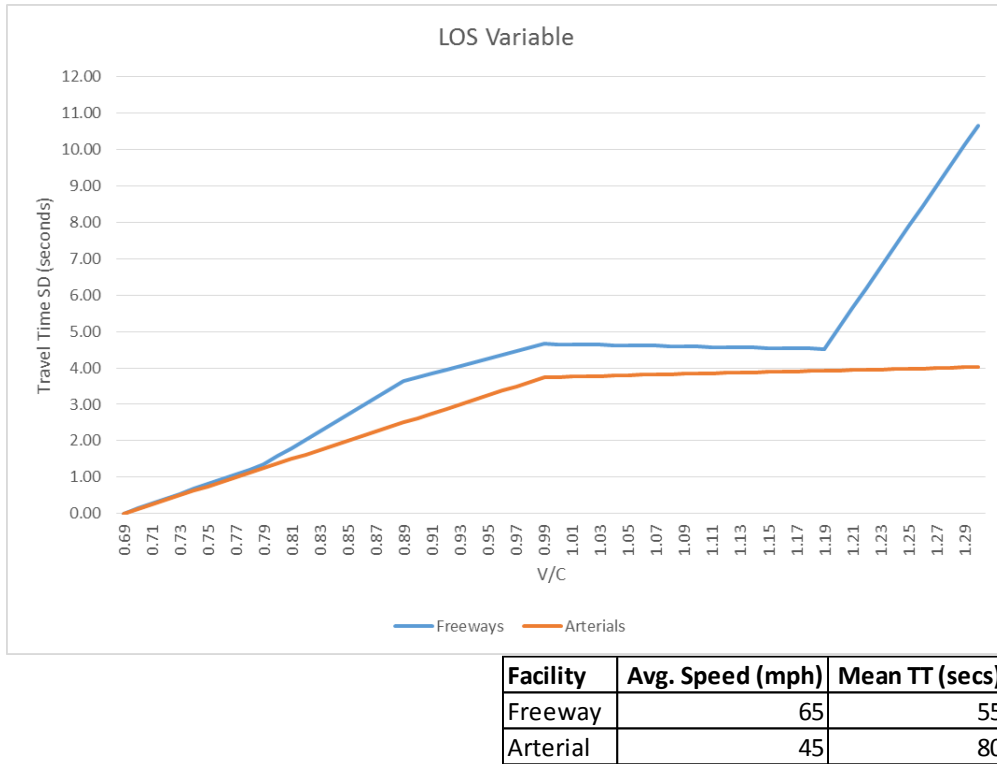
FIGURE 14. LEVEL OF SERVICE PLOT

Speed has a positive effect on travel time variability. Freeway segments with higher speeds (ISPD=70) are generally less reliable (higher travel time SD) as they have a greater potential for speed loss due to recurring congestion.

Similar to LOS variables, time of day shift variables are also additive. So, the contribution from multiple variables is added if applicable to a time of day. In general, as shown in Figure 15, off peak periods (EA, MD, and EV) are more reliable and variability increases as time of day approaches peak periods. The effect is as expected, as off peak periods generally have lower demand, thus facilities operate close to free-flow conditions with a low variability.
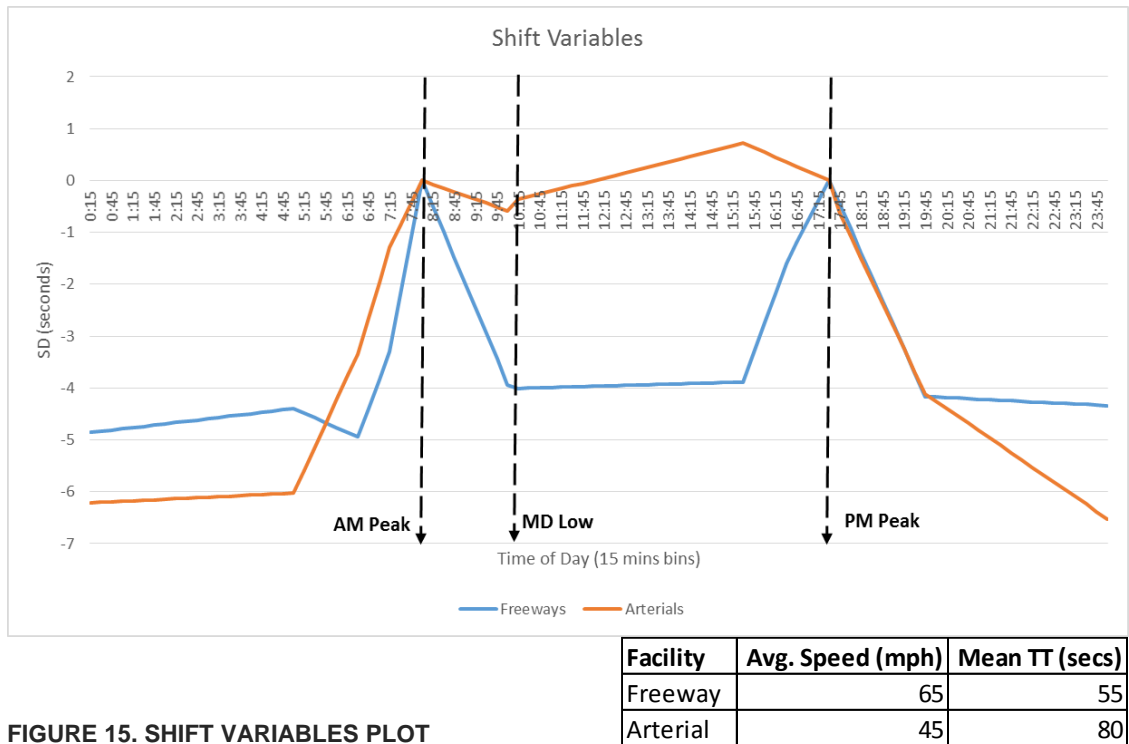
FIGURE 15. SHIFT VARIABLES PLOT

Facility	Avg. Speed (mph)	Mean TT (secs)
Freeway	65	55
Arterial	45	80

As expected, and as shown in Figure 16, the inverse of distance (upstream and downstream) to major intersections has a positive impact on variability, suggesting that segments closer to interchanges are more unreliable. Vehicles entering and exiting freeways at major interchanges can have complicated weaving patterns, which causes vehicles to slow down thus adding more variability to travel time.
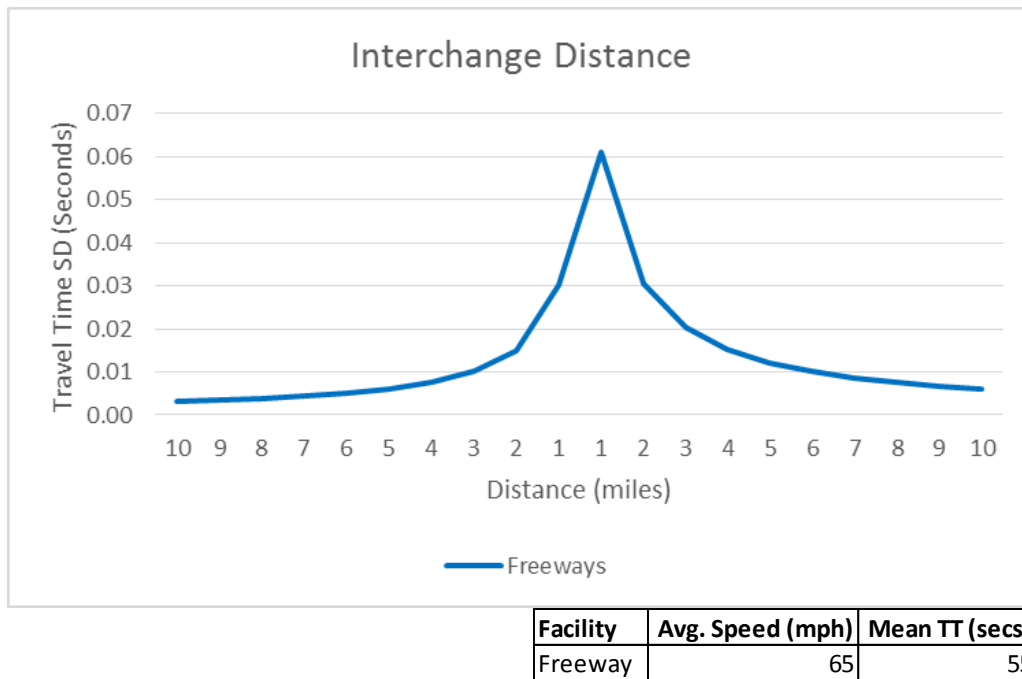
FIGURE 16. INTERCHANGE DISTANCE PLOT

Facility	Avg. Speed (mph)	Mean TT (secs)
Freeway	65	55

Estimation results for arterials are shown in Table 22.

TABLE 22. ESTIMATION RESULTS - ARTERIALS

	Estimate	Std. Error	t value
(Intercept)	0.05466	0.00089	61.62
NumLanesCatTwoLane	0.01036	0.00049	21.22
NumLanesCatThreeLane	0.03612	0.00054	66.39
NumLanesCatFourLanes	0.04470	0.00116	38.44
LOSC.Up	0.15611	0.01442	10.83
LOSF.Low.Up	-0.14492	0.04421	-3.28
ISPD.CatISPD35	0.00757	0.00066	11.45
ISPD.CatISPD40	0.00910	0.00069	13.19
ISPD.CatISPD45	0.00810	0.00067	12.12
ISPD.CatISPD50	-0.00229	0.00071	-3.23
ISPD.CatISPD50More	-0.00462	0.00076	-6.08
BeforeAM.Step1	-0.00537	0.00040	-13.60
BeforeAM.Step2	-0.00317	0.00079	-4.00
BeforeAM.Step3	0.00295	0.00059	5.00
BeforeAM.Step4	0.00547	0.00021	25.93
AfterAM.Step1	-0.00091	0.00014	-6.55
BeforePM.Step1	0.00113	0.00010	11.08
BeforePM.Step3	-0.00178	0.00013	-13.48
AfterPM.Step1	-0.00792	0.00098	-8.05
AfterPM.Step2	0.00249	0.00109	2.29
AfterPM.Step3	0.00366	0.00018	20.88
ICNT.EstSignal	0.00310	0.00029	10.58
ICNT.EstStop	-0.00633	0.00149	-4.24
ICNT.EstRailRoad	0.01277	0.00283	4.52
Adjusted R-Squared		**0.374**	

Travel time variability on arterials increases with more lanes on a segment. More lanes on an arterial likely indicates greater potential for travel time unreliability due to vehicle lane changes.

Compared to freeways, arterials have a flatter effect of level of service (LOS) on travel time unreliability, as shown in Figure 14. Unreliability increases at a steady rate until demand is less than capacity and after that it is pretty steady with a small positive rate.

The arterial facilities with posted speed of 35 mph or higher are more unreliable compared to the facilities with speeds lower than 35 mph. However, facilities are more reliable if posted speeds are 50 mph or more.

Shift variables have a similar effect as in the freeway estimations except the mid-day period being more unreliable, Figure 15.

Compared to no signals, arterial facilities with signals at one of the ends are less reliable, likely due to the variability of encountering a red light and potential signal failure due to turning conflicts and congestion.. Similarly, rail road crossings add to unreliability due to infrequent closed rail road crossings. On the other hand, the presence of stop signs decreases unreliability as the sign requires to always make a stop.

VALIDATION

For the validation dataset, we calculated estimated travel time variability per mean travel time using estimated models. The estimated sdpermean values were compared against the actual sdpermean values in the dataset.

Figure 17 and Figure 18 presents two scatter plots for freeways and other facility classes.
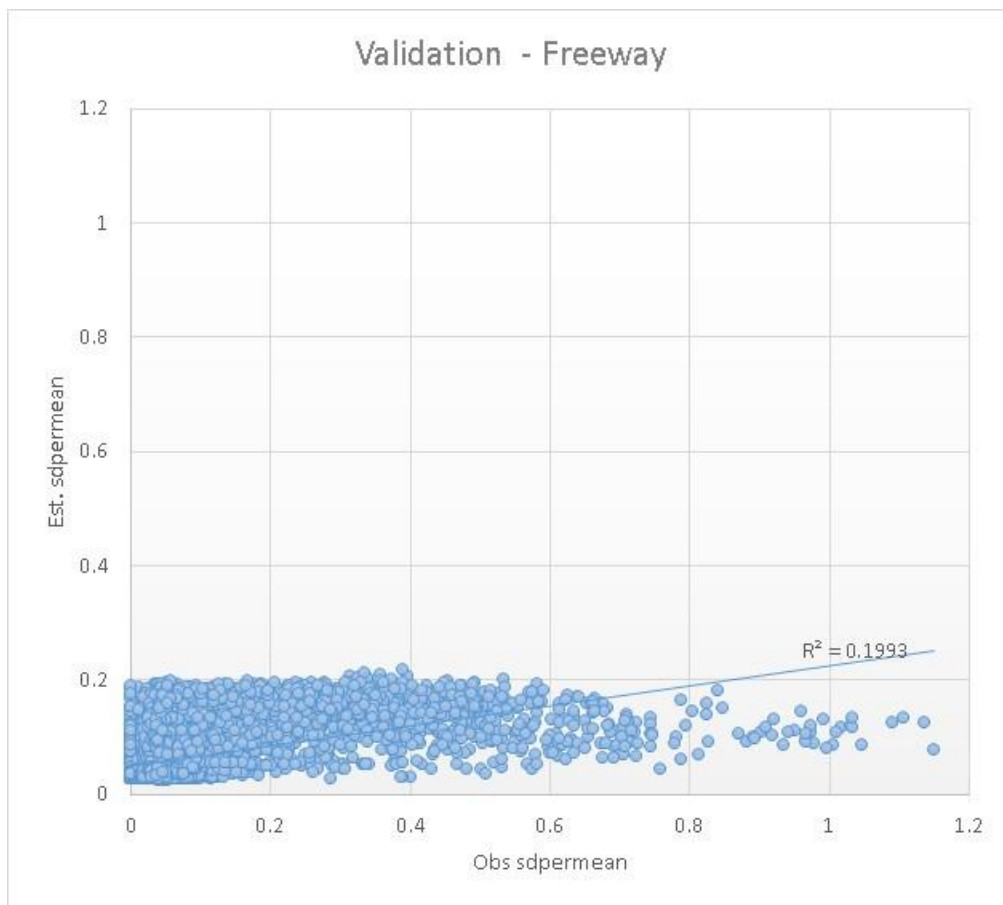
FIGURE 17. REGRESSION MODEL VALIDATION - FREEWAY
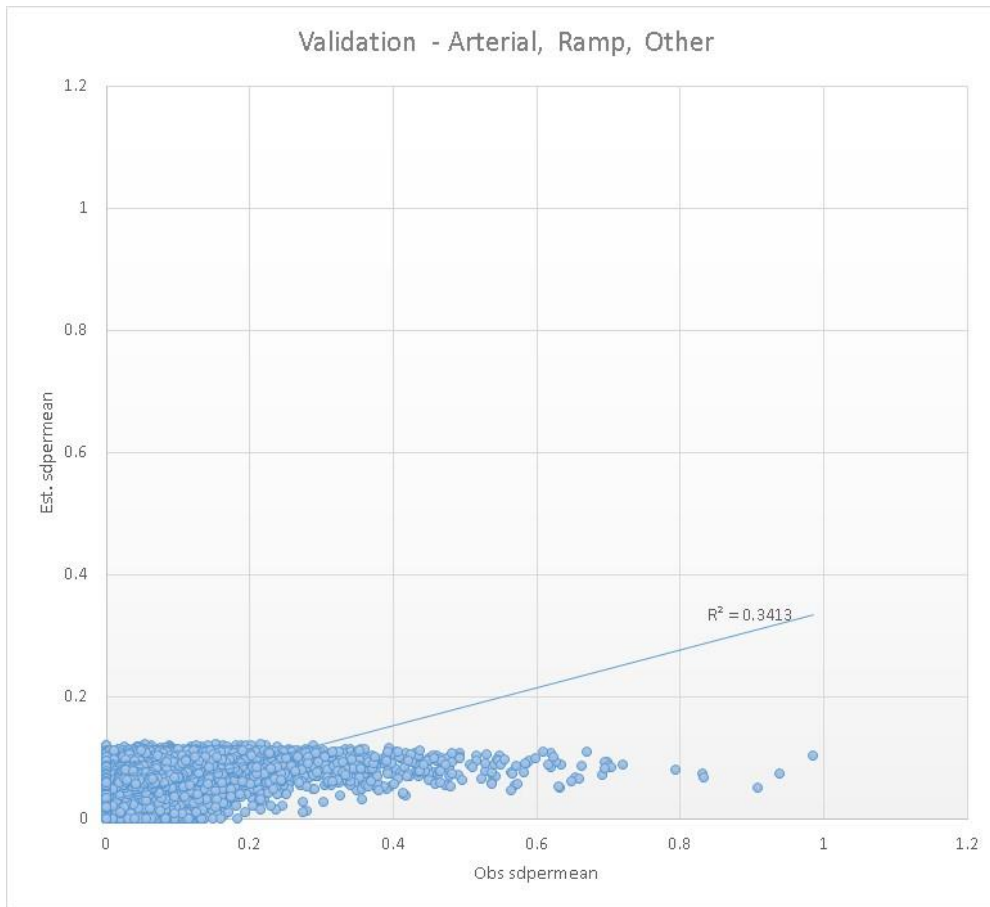
FIGURE 18. REGRESSION MODEL VALIDATION – ARTERIAL, RAMP, AND OTHER

R-squared values are calculated similar to the values from model estimations. For freeways, actual variability per mean travel time goes up to 1.2, however, the estimated values do not go beyond 0.2. This is probably due to aggregation bias in the regression model and in the application of the regression equations. For example, there are only 5 time periods used in auto assignment, and the assignments are static equilibrium. Speeds can never go above free flow in the model. The observed data however is based on 15 minute averages, and the speeds can go both lower and higher than posted; in reality we observe speeds on freeway segments that are well over posted speed. The model doesn't take into account or predict 'non-recurring congestion' which can cause gridlock conditions which we also observed in the data. All of these factors lead the model to a more conservative estimate of unreliability than the observed data, which can be seen in Figure 17 and Figure 18. However, given that the estimated unreliability for the assignment periods is more conservative than the real-world reliability for 15 minute intervals, inclusion of unreliability in assignment is expected to have less of an impact than if the situation was reversed – e.g. when unreliability is over-estimated.

4.2 | ENHANCED VOLUME DELAY FUNCTION (VDF) WITH RELIABILITY

During highway assignment, volume-delay function (VDF) accounts for travel time delays to provide congested travel time on a link. The VDF was modified to reflect the contribution of travel time variability.

The original volume-delay function (VDF) model is shown in Equation 7.

EQUATION 7. ORIGINAL VDF

$$T_f = T_0 * \left[1 + \alpha_i * \left(\frac{V}{C_s} \right)^{\beta_i} \right] + P * \frac{c}{2} * \left(1 - \frac{g}{c} \right)^2 * \left[1 + \alpha_i * \left(\frac{V}{C_i} \right)^{\beta_i} \right]$$

$$C_i = S * \frac{g}{c}$$

The VDF consists of three components:

- Mid-link BPR function
- Uncongested signal delay
- Intersection congestion adjustments

The VDF is modified to include a new reliability component, as shown in Equation **8**.

EQUATION 8. MODIFIED VDF TO INCLUDE RELIABILITY

$$T_{f+r} = T_f + T_f * \left[\sum_{t=1,n} \left(\gamma_t * \frac{v}{c} - t + 0.01 \right) + R \right]$$

Where:
T_{f+r} = Travel time with (un)reliability
T_f = Travel time without (un)reliability
t   = v/c thresholds (C, D, E, F-low, F-high)
γ_t = Coefficients for v\c thresholds
R = non-v\c link (un) reliability

The reliability component is made of two parts:

- LOS unreliability – unreliability from LOS variables
- Static unreliability – unreliability from other variables (lanes, speed, distance to/from interchanges, intersection type) including the intercept

Static unreliability is pre-calculated during the initial model run. As LOS unreliability are calculated using link flows, it is dynamically populated after every iteration of assignment.

As the regression models estimate travel time standard deviation per mean travel time per mile, total reliability from the two components is multiplied by average travel time (from original VDF model).

The reliability implementation is performed by facility type and by five time periods. As mentioned before, regression models are estimated for freeways and arterials only, ramps and other facility types are applied with arterial estimations. The GISDK script "createhwynet.rsc" is modified to add reliability related variables to

the network. LOS fields store estimated coefficients by facility type. The coefficients are multiplied with v/c ratios during VDF model calculations to get the LOS component of the unreliability.

A macro is added to calculate upstream and downstream distances to major interchanges. Output of the macro is read-in to populate distance fields in the database.

Now the model skims an additional reliability matrix for each mode and reads them directly in tour and trip model choice UECs. Note that it would be ideal to treat model reliability consistently across modes; for example, if we use LOS proxy for reliability, a weighted time skim could also be created for transit, such that non-fixed-guideway routes will experience weighted times according to the congestion on the underlying street network. However, after implementing reliability for auto modes, the magnitude of travel time reliability came out relatively small (for more information, refer 'Skimming Reliability' under Section 6.0). The results suggest that the magnitude would be even smaller for transit mode. Therefore, transit skimming updates were not performed.

4.3 | SKIMMING RELIABILITY

We calculate reliability as the standard deviation of travel time at a link level. Calculations of total travel time variability between each OD pair requires summing the variability on each link along the least-cost path. However, travel time link variability cannot be simply aggregated because standard deviation is not additive. On the other hand, variance is additive. To demonsrate, an example is presend in Table 23.

TABLE 23. EXAMPLE OF TRAVEL TIME VARIABILITY CALCULATIONS

Link	Travel Time Observations (min)					Average time	Standard Deviation	Variance
	1	2	3	4	5			
1	2	5	1	2	1	2.2	1.6	2.7
2	5	7	9	9	9	7.8	1.8	3.2
3	8	8	8	13	13	10	2.7	7.5
4	3	1	3	3	3	2.6	0.9	0.8
5	7	2	4	2	7	4.4	2.5	6.3
6	2	3	2	2	3	2.4	0.5	0.3
7	5	6	6	6	5	5.6	0.5	0.3
8	9	9	9	10	7	8.8	1.1	1.2
9	5	5	5	5	5	5	0.0	0.0
10	3	2	1	2	2	2	0.7	0.5
Total	49	48	48	54	55	50.8	12.5	22.8

In the example above, the OD path consists of 10 links. Each link has 5 travel time observations. The standard deviation across all observations (links) comes out to be 3.1 minutes. Now, standard deviation of travel time on each link is calculated and added up to be 12.5 mins. On the other hand, the square root of sum of travel time variance on all links is calculated as 4.8 mins which is much closer to the standard deviation across all observations than simply adding up the link standard deviation. Note that variance is additive only under the assumption of independence of travel times variability across links; although we do not believe travel time variability is in fact independent, we ignore this property for the sake of model simplicity. Furthermore, we can find no empirical evidence of travel time variability link dependence in the literature, and estimating the correlation across links would require the use of a time-dependent path-finding algorithm through a network populated with observed data which is beyond the scope of this project.

Since standard deviation (variability) is not additive along link paths, variance[5] of travel time (square of variability) is skimmed and the final skim values are calculated as the square-root of the skimmed variance.

To determine magnitude of travel time variability in the model, a scatter plot of travel time and travel time variability for all OD pairs in San Diego county is created, shown in Figure 19. To display this large dataset (4996x4996 zone pairs), travel time and variability are first integerized. In general, variability is higher with higher travel time. The maximum amount of variability for any zone pair is 2.8 minutes, also see Table 24.

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[5] Standard deviation is not additive but variance is.
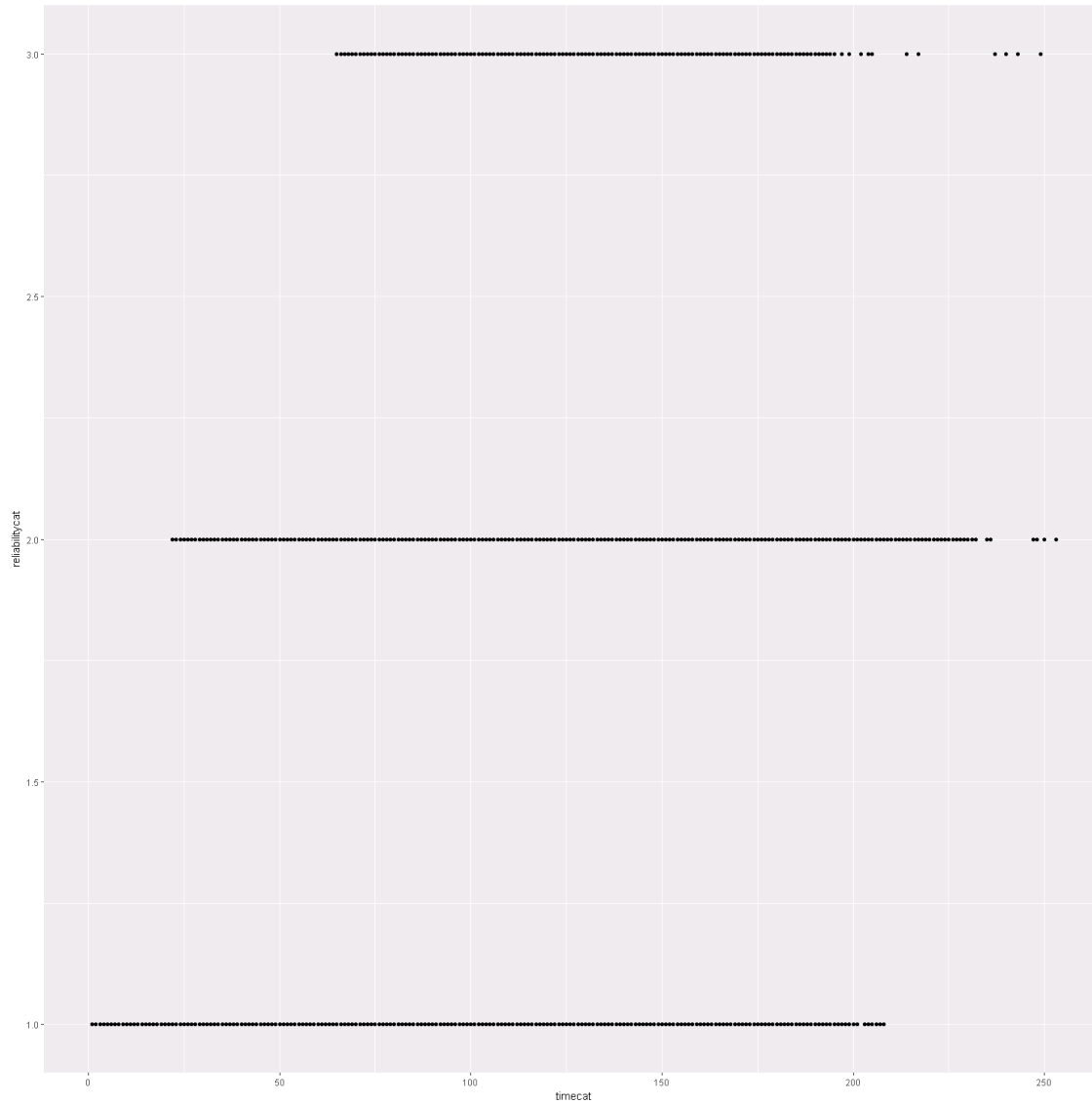
FIGURE 19. TRAVEL TIME VS VARIABILITY (DA TOLL, AM, LOW VOT)

TABLE 24. TRAVEL TIME AND VARIABILITY STATISTICS (DA TOLL, AM, LOW VOT)

	Time	Variability	ratio=Variability/time
Count	24955020	24955020	24955020
min	0.127	0.000	0.000
max	252.885	2.814	0.102
median	47.697	0.767	0.016
mean	50.850	0.7801	0.016
std.dev	26.801	0.379	0.004
var	718.270	0.144	0.000

A plot of average variability in one-minute travel time bins looks like a curve confirming the above observation of higher (variability with higher travel time (Figure 20). The points on the right-hand side of the plot as travel time approaches 200 minutes are associate with external stations in eastern San Diego county, where the external link is coded with a very long link length (resulting in a high travel time) but with little demand and therefore relatively lower variability.
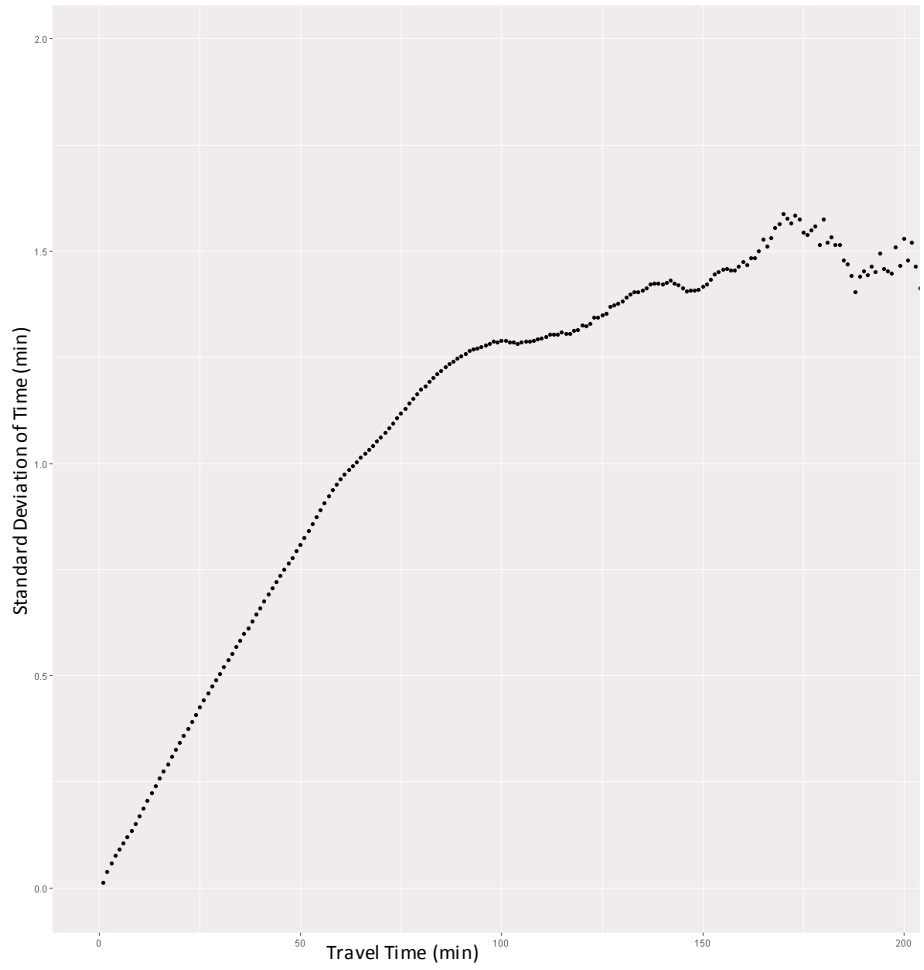
FIGURE 20. TRAVEL TIME VS AVERAGE VARIABILITY

5.0 DEMAND MODEL ENHANCEMENTS

5.1 | MODEL OVERVIEW

There are a number of different travel markets represented in the SANDAG travel demand model system, including typical daily resident travel, travel by Mexican residents, visitor travel, internal-external travel, and so on. Many of the models used to represent demand are simulation-based models, such as activity-based or tour-based approaches. Some of the travel models are aggregate three or four-step representations of travel. Table 25 lists the SANDAG travel markets along several key dimensions.

There are two broad types of models and three specific types of models identified in Table 25. Disaggregate models refer to models whose demand is generated via a stochastic simulation paradigm. Both activity-based and tour-based models are simulation-based, which rely upon a synthetic population to generate travel and stochastic processes to choose alternatives and output disaggregate demand in the form of tour and trip lists.

Only the resident travel model is an activity-based model, in which all tours and activities are scheduled into available time windows across the entire day. The approach recognizes that a person can be in only one place at one time and their entire day is accounted for in the model. A tour-based treatment is used for a number of other special travel markets. Tour-based models do not attempt to model all travel throughout the day for each person; rather, once tours are generated they are modeled independently of each other. For example, it is possible that a visitor generates two tours where the outbound and return time periods for each tour are scheduled consistently but the starting time of the second tour is before the return time of the first tour. A tour-based model does not attempt to schedule all travel into available time windows.

Aggregate models rely upon probability accumulation processes to produce travel demand and output trip tables. The commercial vehicle model and certain external travel models are aggregate.

The disaggregate activity-based and tour-based models output trip lists with 30-minute temporal resolution, identifying the departure time period of each trip. Note that the three time periods from 3:00 A.M. to 4:59 A.M. are aggregated into one time-of-day alternative, and the seven time periods from 12:00 A.M. to 3:29 A.M. are also aggregated, for a total of 40 explicit time periods. The implied duration of each out-of-home activity, which can be found by subtracting the departure time from the previous activity from the departure time for the activity, implicitly includes the travel time to the activity.

TABLE 25: TRAVEL MARKETS IN SANDAG TRAVEL DEMAND MODEL SYSTEM

Segment	Travel Market	Description	Model Type	Temporal Resolution	Spatial Resolution	Vehicle classes
1	San Diego resident travel (internal)	Average weekday travel made by San Diego residents within San Diego County	Disaggregate activity-based	30-minute	MGRA	8 (classes 1 through 8 in Table 27)
2	San Diego resident travel (internal-external)	Average weekday travel by San Diego residents between San Diego County and other county\Mexico	Disaggregate tour-based	30-minute	Internal MGRA – external cordon TAZ	8 (classes 1 through 8 in Table 27)
3	Mexican resident travel (external-internal and internal-internal)	Average weekday travel by Mexican residents into, out of, and within San Diego County	Disaggregate tour-based	30-minute	Internal MGRA – external cordon TAZ	8 (classes 1 through 8 in Table 27)
4	Overnight visitor	Average weekday travel made by overnight visitors to San Diego county	Disaggregate tour-based	30-minute	MGRA	8 (classes 1 through 8 in Table 27)
5	Airport passenger	Average weekday travel made by air passengers and related trips such as taxis to/from airport	Disaggregate Trip-based	30-minute	MGRA	8 (classes 1 through 8 in Table 27)

Segment	Travel Market	Description	Model Type	Temporal Resolution	Spatial Resolution	Vehicle classes
6	Special events	Special event travel; not average but event-specific	Disaggregate Trip-based	30-minute	MGRA	8 (classes 1 through 8 in Table 27)
7	External-External	Average weekday travel with neither origin nor destination in San Diego County	Aggregate Trip-based	5 time periods (see Table 26)	External cordon TAZ	2 (classes 1 and 2 in Table 27)
8	Other U.S.-Internal travel	Average weekday external-internal trips made by non-San Diego and non-Mexican residents	Aggregate Trip-based	5 time periods (see Table 26)	External cordon TAZ – Internal TAZ	2 (classes 1 and 2 in Table 27)
9	Commercial Vehicle Trips	Average weekday vehicle trips made for commercial purposes (including light truck goods movements and service vehicles)	Aggregate Trip-based	5 time periods (see Table 26)	TAZ	2 (classes 1 and 2 in Table 27)
10	Heavy truck trips	Average weekday vehicle trips for 3 weight classes	Aggregate Trip-based	5 time periods (see Table 26)	TAZ	6 (classes 9 through 14 in Table 27)

Aggregate models output demand in the five broad time periods, as shown in Table 26, which are also consistent with the periods used in highway and transit assignment. Trip tables from disaggregate model output are created by aggregating trip lists into these periods prior to assignment, and applying occupancy factors to convert person trips to vehicle trips.

TABLE 26: TIME PERIODS IN EQUILIBRIUM CAPACITY-RESTRAINT ASSIGNMENT

Period	Duration
Early A.M.	3:00 A.M. to 5:59 A.M.
A.M. Peak	6:00 A.M. to 8:59 A.M.
Midday	9:00 A.M. to 3:29 P.M.
P.M. Peak	3:30 P.M. to 6:59 P.M.
Evening	7:00 P.M. to 2:59 A.M.

Vehicles are assigned in TransCAD using a multi-class equilibrium capacity-restraint assignment, using 14 classes as shown in Table 27 along with the corresponding value of time and passenger car equivalent for each class. The assignment process utilizes a volume-delay function that includes both mid-block and intersection delay. The time returned by this volume-delay function is converted to cost using the value of time and auto operating cost (currently set at 19.8 cents per mile) and toll cost are added in order to find minimum path through the network.

TABLE 27: VEHICLE CLASSES USED IN EQUILIBRIUM CAPACITY-RESTRAINT ASSIGNMENT

Number	Class	Description	Value of time	Passenger-Car Equivalent
1	Drive-alone non-toll eligible	Single occupant vehicles not allowed to utilize toll facilities for their route choice	$30.00/hour	1.0
2	Drive-alone toll eligible	Single occupant vehicles allowed to utilize toll facilities for their route choice	$30.00/hour	1.0
3	Shared-2 non-toll, non-HOV eligible	Two occupant vehicles not allowed to utilize toll facilities or High-Occupant Vehicle (HOV) lanes for their route choice	$30.00/hour	1.0
4	Shared-2 non-toll, HOV eligible	Two occupant vehicles not allowed to utilize toll facilities but	$30.00/hour	1.0

		allowed to utilize HOV lanes for their route choice		
5	Shared-2 toll, HOV eligible	Two occupant vehicles allowed to utilize toll facilities and HOV lanes for their route choice	$30.00/hour	1.0
6	Shared 3+ non-toll, non-HOV eligible	Three or more occupant vehicles not allowed to utilize toll facilities or High-Occupant Vehicle (HOV) lanes for their route choice	$30.00/hour	1.0
7	Shared 3+ non-toll, HOV eligible	Three or more occupant vehicles not allowed to utilize toll facilities but allowed to utilize HOV lanes for their route choice	$30.00/hour	1.0
8	Shared 3+ toll, HOV eligible	Three or more occupant vehicles allowed to utilize toll facilities and HOV lanes for their route choice	$30.00/hour	1.0
9	Light-heavy trucks, non-toll eligible	Trucks weighing between 8,500 and 14,000 pounds, not allowed to utilize toll facilities	$30.00/hour	1.3
10	Medium-heavy trucks, non-toll eligible	Trucks weighing between 14,000 and 33,000 pounds, not allowed to utilize toll facilities	$30.60/hour	1.5
11	Heavy-heavy trucks, non-toll eligible	Trucks weighing more than 33,000 pounds, not allowed to utilize toll facilities	$43.20/hour	2.5
12	Light-heavy trucks, toll eligible	Trucks weighing between 8,500 and 14,000 pounds, allowed to utilize toll facilities	$30.00/hour	1.3
13	Medium-heavy trucks, toll eligible	Trucks weighing between 14,000 and 33,000 pounds, allowed to utilize toll facilities	$30.60/hour	1.5
14	Heavy-heavy trucks, toll eligible	Trucks weighing over 33,000 pounds, allowed to utilize toll facilities	$43.20/hour	2.5

There are two aspects to implementation of the enhancements described in Chapter 2.0; demand model enhancements and supply model enhancements. Demand model enhancements involve modifications to CT-

RAMP software to ensure sensitivity to pricing and reliability in tour and stop frequency, destination, scheduling, and mode choice models. Supply model enhancements involve changes to TransCAD GISDK code to ensure that level-of-service matrices and vehicle paths are appropriately sensitive to pricing and reliability network attributes. Both aspects are implemented to ensure a consistent set of responses (see Appendix D for code changes). The details of the demand model enhancements are described below. The supply model enhancements are described in the next chapter.

5.2 | DISTRIBUTED TIME SENSITIVITY AND CONTINUOUS COST COEFFICIENTS

As described above, the SHRP C04 report recommends the use of distributed travel time sensitivity along with cost scaled by a continuous function of household income and a parameter that reflects cost sharing across travel party members.

Our approach to implementation of these recommendations includes multiplying the originally-estimated travel time coefficient by a unique travel time sensitivity drawn for each traveler from a distribution. The SHRP C04 report provides a graph of sample log-normally distributed travel time distributions but does not recommend specific mean and standard deviation parameters controlling the shape of the distributions. Our first implementation of random travel time parameters in the SANDAG model were based upon recent work performed for the Sacramento Area Council of Governments activity-based model. However, upon comparison of the resulting value-of-time distributions from their parameters compared to stated preference data (reports not yet published) we use a lognormal distributed parameter for work tours with mean 1.0 and standard deviation 0.7, and mean 1.0 and standard deviation 0.6 for non-work tours. Work and non-work time sensitivities are first sampled for every person in the synthetic population, and then used as multipliers of estimated travel time coefficients for tour and trip mode choice models for San Diego residents and Mexican resident travelers. For fully joint tours, we take the time sensitivity from the oldest participating member for the entire tour.

We adopt cost coefficients directly from the SHRP C04 report for San Diego residents. In order to prevent values-of-time on the extremes of the distribution and undefined values-of-time, we use a minimum household income of $1000 in the calculation of the cost coefficient.

Resulting value-of-time distributions for individual work tours, individual non-work tours, and joint tours are shown in Figure 21. Joint tours exhibit the largest variance, likely due to the effect of a smaller cost coefficient related to number of tour participants over which the cost of travel is spread. Individual non-mandatory tours exhibit the least variance, and the lowest mean value-of-time, due to the relatively lower time sensitivity for non-mandatory travel which includes shopping and recreational tours. Joint tours exhibit the largest variance, likely due to the effect of a smaller cost coefficient related to number of tour participants over which the cost of travel is spread. Individual non-mandatory tours exhibit the least variance, and the lowest mean value-of-time, due to the relatively lower time sensitivity for non-mandatory travel which includes shopping and recreational tours.
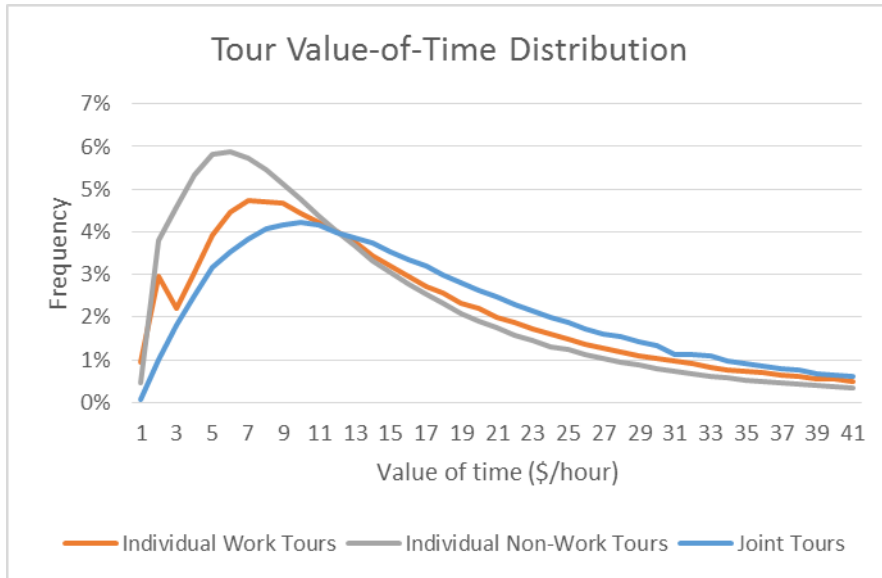
FIGURE 21. TOUR VALUE-OF-TIME DISTRIBUTION

We also explore mean, standard deviation, and percentiles of value-of-time for tours by chosen tour mode and trips by chosen trip mode, as shown in Table 28 and Table 29.

TABLE 28. VALUE-OF-TIME STATISTICS – TOURS BY TOUR MODE ($/HOUR)

Tour Mode	Mean	Std. Dev.	p1	p10	p25	p50	p75	p90	p99
Drive-alone	13.38	12.28	0.59	3.18	5.81	10.07	16.97	26.99	60.22
Shared 2	19.75	18.01	1.39	5.08	8.65	14.78	24.82	39.63	88.91
Shared 3+	25.35	24.19	1.75	6.30	10.83	18.62	31.68	51.05	118.71
Non-motorized	7.64	8.67	0.39	1.25	2.73	5.27	9.48	16.03	41.37
Walk-transit	6.58	5.53	0.57	1.86	3.09	5.14	8.33	12.78	27.52
PNR-transit	12.01	11.68	1.36	3.23	5.21	8.82	14.78	23.75	60.17
KNR-transit	7.67	6.10	1.11	2.43	3.72	5.95	9.61	14.84	30.84
School bus	5.51	4.24	0.38	1.45	2.69	4.49	7.16	10.69	20.83
Total	**15.93**	**17.17**	**0.62**	**2.95**	**5.81**	**10.99**	**19.98**	**33.76**	**83.05**

TABLE 29. VALUE-OF-TIME STATISTICS – AUTO TRIPS BY TRIP MODE ($/HOUR)

Trip Mode	Mean	Std. Dev.	p1	p10	p25	p50	p75	p90	p99
Drive-Alone, Non-Toll	15.39	15.53	0.64	3.48	6.31	11.1	19.16	31.41	75.79
Drive-Alone, Toll Eligible	22.96	19.61	3.01	7.18	10.95	17.96	28.03	43.91	98.16
Shared 2, Non-Toll	20.02	18.93	1.37	4.82	8.47	14.75	25.13	40.68	92.82
Shared 2, Toll Eligible	33.03	28.80	4.83	9.68	15.16	24.44	40.46	65.62	149.79
Shared 3+, Non-Toll	23.92	22.42	1.94	6.32	10.5	17.71	29.75	47.62	110.95
Shared 3+, Toll Eligible	35.59	32.56	5.10	9.79	15.39	25.32	43.78	74.98	164.18
Total	**17.76**	**17.86**	**0.8**	**4.01**	**7.2**	**12.75**	**22.16**	**36.47**	**87.18**

We see that tour and trip values-of-time logically increase with respect to occupancy due to cost sharing. Walk-transit and kiss-and-ride transit values of time tend to be lower than park-and-ride transit. Value of time comparisons by trip mode demonstrate that travelers who choose toll-eligible paths have a much higher value-of-time than non-toll eligible trips. This is partly a function of the fact that toll paths are more prevalent for mandatory tours\trips in peak periods. However, it is logical that the value-of-time for toll road users would be higher than that of non-toll road users. Finally, we note that average tour value-of-time is approximately $16.00/hour and average trip value-of-time is $17.76.

We also utilize the recommended parameters on travel time reliability, which is specified as standard deviation of travel time per mile. Travel time, cost, and reliability parameters used in tour and trip mode choice models by purpose are given in Table 30.

TABLE 30: TOUR AND TRIP MODE CHOICE TRAVEL TIME, COST, AND RELIABILITY PARAMETERS BY TOUR PURPOSE

	Work	University	School	Maintenance	Discretionary	Work-Based
Tour Mode Choice						
Travel Time	-0.016	-0.016	-0.01	-0.017	-0.015	-0.032
Cost OB	-1.25	-0.523	-0.523	-0.523	-0.523	-0.523
Cost IB	-1.44					
Reliability OB SD(min)/Dist(mile)	-0.224	-0.192	-0.120	-0.204	-0.180	-0.384
Reliability IB SD(min)/Dist(mile)	-0.192					
Trip Mode Choice						

Travel Time	-0.032	-0.032	-0.02	-0.034	-0.03	-0.06
Cost OB	-1.25	-0.523	-0.523	-0.523	-0.523	-0.523
Cost IB	-1.44					
Reliability OB SD(min)/Dist(mile)	-0.224	-0.384	-0.240	-0.408	-0.360	-0.720
Reliability IB SD(min)/Dist(mile)	-0.192					

6.0   SUPPLY MODEL ENHANCEMENTS

Key aspects of supply model enhancements include changes to skimming and assignment procedures to support multiple income classes, incorporation of reliability (already described above), and updates to toll costs. Additionally, the project tested gate-to-gate tolling features in TransCAD 6.0.

6.1 | ASSIGNMENT USER CLASSES BASED ON VALUE-OF-TIME

The project implemented three user classes with value-of-time ranges based upon an analysis of the distribution of base-year value-of-time represented in the demand models as described in Section 5. Implementation of value-of-time specific skimming and assignment required modifications to several GISDK scripts, as follows:

- **createhwynet.rsc**: Generates link fields required for skimming based on generalized cost. We will modify this script to calculate generalized cost based upon different value-of-time ranges.

- **createtrnroutes.rsc**: Generates transit networks and link fields required for skimming transit time. We will modify this script to calculate generalized cost based upon different value-of-time ranges.

- **createTODTable.rsc**: This script adds together trip tables from all model components (resident internal travel, resident internal-external travel, Mexican travel, etc.) and creates trip tables for assignment. We will modify this script to create value-of-time specific trip tables for assignment.

- **hwyskim.rsc**: This script creates highway skims by time-of-day and occupancy\facility (general purpose, non-toll HOV, and toll-eligible\HOV-eligible) class; we will extend the scripts to create skims by value-of-time classes.

- **hwyassign.rsc:** This script assigns highway trip tables by time-of-day and occupancy\facility class; we will extend the user classes to consider value-of-time classes.

- **trnassign.rsc**: This script assigns transit trip tables by time-of-day, access mode (walk, park-and-ride, kiss-and-ride) and transit line-haul mode (local bus, express bus, bus rapid transit, light-rail, commuter rail). We do not expect to assign transit demand by value-of-time bin.

Other scripts were also modified as needed to account for skim and\or trip table changes related to value-of-time classes. With three value-of-time bins, the number of auto skims increased from 20 per period to 60 per period, or from a total of 100 auto skims to a total of auto 300 skims. This required increasing the RAM in each worker node by approximately 20 gigabytes.[6] The project did not skim or assign transit by value-of-time bin, since the transit path-builder used in the SANDAG CT-RAMP model is based upon stop-pair and variation in stop-to-stop paths by value-of-time is not anticipated to be significant.

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[6] In the Java programming language, each array is an object whose data members include a header record that stores information about the object length and a set of data elements sized to the length of the array. Due to byte alignment, the memory required for each object must be rounded up to the nearest multiple of eight bytes. A two dimensional matrix is stored as an array of arrays. The total memory required for a two dimensional array in Java is therefore equal to the memory required for an array of the first dimension and the memory required for each array of the second dimension. For a square matrix of zones, the calculation is roughly equivalent to the following (without rounding up):

bytes = (zones + 1) * (header_size + zones * element_size)

Since the structure of non-resident travel models is not modified in this project, we mapped the skims used in each model, and the trip tables written by each model, to a specific value-of-time bin implemented in skimming and assignment. For example, the value-of-time for Mexican residents is fairly low, at approximately $2.40 for trip mode choice. Consequently, we mapped this travel market to the low value-of-time bin.

Table 31 shows values of time for all special market models in the SANDAG model system based on trip mode choice coefficients (or toll diversion coefficients for external-internal, commercial vehicle, and heavy truck models).

TABLE 31: VALUE OF TIME FOR SPECIAL TRAVEL MARKET MODELS

Market	Trip Purpose	Income Range	Value of time ($\hr)
CrossBorder	All	All	$ 2.40
Airport	Resident - Business	< $25k	$ 6.01
Airport	Resident - Business	$25-$50k	$ 18.03
Airport	Resident - Business	$50-$75k	$ 30.05
Airport	Resident - Business	$75-$100k	$ 42.07
Airport	Resident - Business	$100-$125k	$ 54.09
Airport	Resident - Business	$125-$150k	$ 66.11
Airport	Resident - Business	$150-$200k	$ 84.13
Airport	Resident - Business	$200k+	$ 120.19
Airport	Resident - Personal	< $25k	$ 3.00
Airport	Resident - Personal	$25-$50k	$ 9.01
Airport	Resident - Personal	$50-$75k	$ 15.02
Airport	Resident - Personal	$75-$100k	$ 21.03
Airport	Resident - Personal	$100-$125k	$ 27.04
Airport	Resident - Personal	$125-$150k	$ 33.05
Airport	Resident - Personal	$150-$200k	$ 42.07
Airport	Resident - Personal	$200k+	$ 60.10
Special Event	All	< $30k	$ 2.40
Special Event	All	$30k-$60k	$ 5.45
Special Event	All	$60k-$100k	$ 8.57

Special Event	All	$100k+	$ 20.00
Visitor	All	< $30k	$ 2.40
Visitor	All	$30k-$60k	$ 5.45
Visitor	All	$60k-$100k	$ 8.57
Visitor	All	$100k+	$ 20.00
External-Internal Vehicles	Work	All	$ 9.00
External-Internal Vehicles	Non-Work	All	$ 13.70
Heavy Trucks	All	NA	$ 30.00
Commercial Vehicles	All	NA	$ 30.00

6.2 | TOLL COST

Currently the SANDAG model represents all toll costs at a link level, where the link costs are based on the average gate-to-gate tolls. A good approach to using gate-to-gate cost is treating toll calculations as an optimization problem where link-level tolls are calculated to best match the gate-to-gate movements that utilize them. The optimization approach minimizes an objective function (the difference between estimated and observed toll) by varying the link tolls whilst satisfying applied constraints (minimum toll), if any. For a toll optimization problem, the objective function can be constructed in two ways:

- Method 1 – an additive function by varying tolls on entry and exit links
- Method 2 – an additive function by varying tolls on toll links that are traversed between consecutive entry-exit pairs

The two methods are different in respect to where the tolls are assigned. The method 1 applies tolls on entry and exit links (on/off ramps) onto a toll facility, whereas the method 2 applies tolls on the toll facility links.

SR125 TOLL ROAD

The SR125 toll facility tolls are fixed costs and assigned on entry and exit links. The tolls experienced in the model system are compared with the observed toll. A GISDK script extracts estimated tolls from toll skims using OD pairs corresponding to entry-exit gates.

The estimated tolls for drive-alone (DA) mode during AM period are compared with the observed tolls and presented in Table 32, Table 33, Figure 22, and Figure 23.

TABLE 32. SR125 TOLL COMPARISON – DA AM NB

Gate Pairs		Obs. Toll		Est. Tolls	
From	To	Wtd.	Low	Med	High
Otay Mainline Toll Plaza	Birch Road	222	240	240	240
Otay Mainline Toll Plaza	Olympic Parkway	222	236	236	236
Otay Mainline Toll Plaza	Otay Lakes Road	222	241	241	241
Otay Mainline Toll Plaza	East H Street	226	242	242	242
Otay Mainline Toll Plaza	SR54	279	0	356	356
Birch Road	Olympic Parkway	95	0	0	0
Birch Road	Otay Lakes Road	95	0	0	76
Birch Road	East H Street	95	77	77	77
Birch Road	SR54	221	191	191	191
Olympic Parkway	Otay Lakes Road	95	0	0	0
Olympic Parkway	East H Street	95	0	0	0
Olympic Parkway	SR54	221	190	190	190
Otay Lakes Road	East H Street	95	0	0	75
Otay Lakes Road	SR54	221	189	189	189
East H Street	SR54	221	142	190	190
San Miguel Ranch Road	SR54	159	0	142	142

TABLE 33. SR125 TOLL COMPARISON – DA AM SB

Gate Pairs		Obs. Toll		Est. Tolls	
From	To	Wtd.	Low	Med	High
SR54	San Miguel Ranch Road	159	0	0	145
SR54	East H Street	221	0	194	194
SR54	Otay Lakes Road	221	0	194	194
SR54	Olympic Parkway	221	193	193	193
SR54	Birch Road	221	195	195	195
SR54	Otay Mainline Toll Plaza	279	358	358	358
East H Street	Otay Lakes Road	95	0	0	0
East H Street	Olympic Parkway	95	0	0	0
East H Street	Birch Road	95	75	75	75
East H Street	Otay Mainline Toll Plaza	226	238	238	238
Otay Lakes Road	Olympic Parkway	95	0	0	0
Otay Lakes Road	Birch Road	95	0	76	76
Otay Lakes Road	Otay Mainline Toll Plaza	222	239	239	239
Olympic Parkway	Birch Road	95	0	0	0
Olympic Parkway	Otay Mainline Toll Plaza	222	239	239	239
Birch Road	Otay Mainline Toll Plaza	222	239	239	239

As expected, more toll paths are available for higher VOT category with high VOT category seeing the most toll paths. The tolls experienced by the high VOT category are graphically compared with the observed tolls and the plots are shown in Figure 22 and Figure 23.
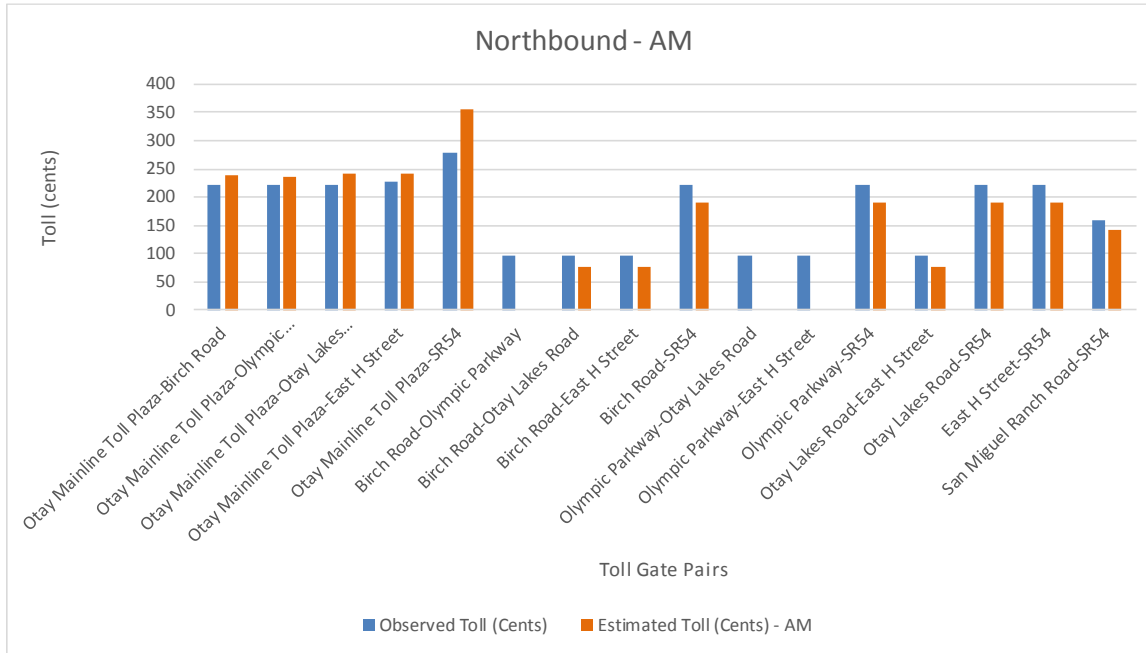
FIGURE 22. SR125 DRIVE-ALONE TOLLS DURING AM PERIOD IN NB DIRECTION
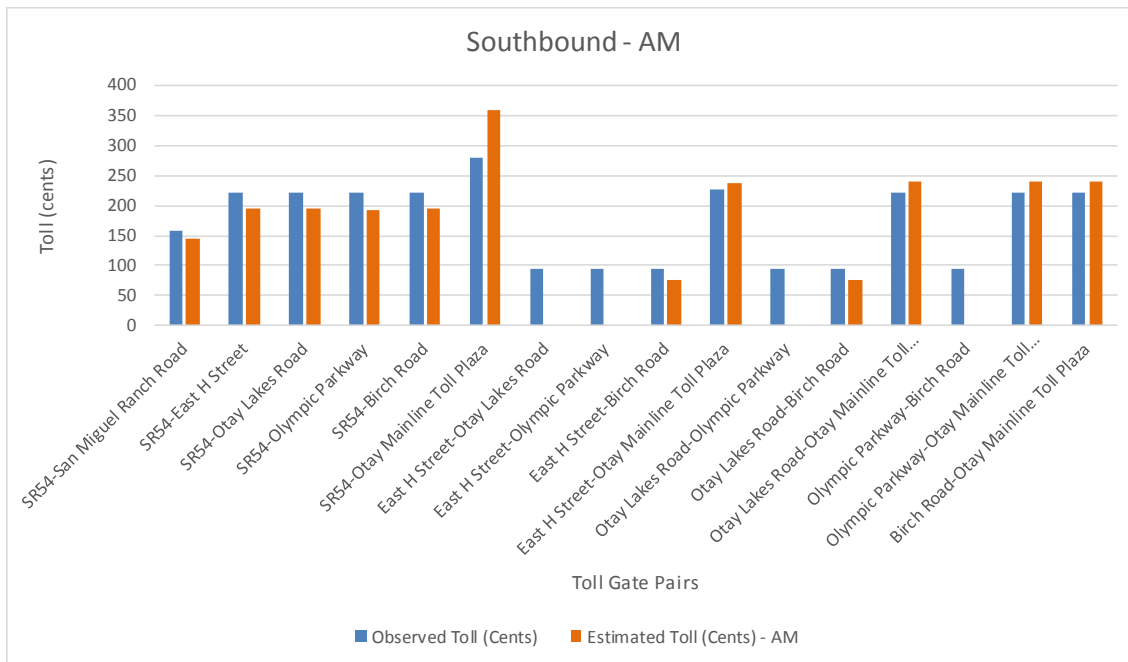
FIGURE 23. SR125 DRIVE-ALONE TOLLS DURING AM PERIOD IN SB DIRECTION

In general, the toll values in the model match well with the observed tolls. SR54 to Otay Mainline Toll Plaza pair has higher estimated tolls (in both directions) Also, a few entry-exit pairs could not find a toll path, suggesting that the toll facility does not offering significant time savings compared to the observed cost.

I15 MANAGED LANE

The I15 managed lane facility was coded with a flat per-mile toll rate for each of the three time periods: AM, PM, and OP. Toll cost on a link is equal to the multiplication of toll rate with the link length. Peak periods (AM and PM) use the corresponding toll rates and off-peak periods (EA, MD, and EV) use the same toll rate of OP period. A comparison of skimmed tolls with the observed model showed lower tolls in the model system. As lower tolls may induce more toll demand on the facility, new tolls were calculated using the optimization approach described above (gate-to-gate cost approach is not viable due to runtime concerns).

Both optimization methods were tried in calculating estimated tolls that most closely match the observed average tolls by time period, direction, and entry/exit gate. An optimization problem is set up by constructing the objective function as the sum of absolute difference between estimated and observed tolls over all possible entry-exit pairs on the I15 managed lane facility. Tolls on a set of links (as per method) were used as the variables in the problem. A constraint of each entry exit pair toll to be at-least 50 cents was also applied. In all, 20 optimization problems were constructed for 2 methods, 2 directions, and 5 time periods. The Excel LP solver is used to solve the optimization problems. The spreadsheet "I15_TollOptimization.xlsx" contains the solutions and is provided to SANDAG.

Method 1 worked better for off-peak periods and directions, while Method 2 worked better for peak period and directions (NB PM and SB AM). [7]

The updated model system produced improved tolls when compared with the observed tolls on the facility. The NB direction tolls by entry-exit gate matched well as shown in Figure 24. (Plots of all time periods are provided in Appendix G)

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[7] The current SANDAG model system gets tolls from the TCOVED file 'tcov.e00' input the model. However, updating the TCOVED file required significant effort and time, which could affect project timelines. Therefore, a GISDK script is used to code the new tolls. A GISDK macro is added to 'createhwynet.rsc' to make the new tolls available to the model system. The macro selects the best method corresponding to a period while setting tolls on I15 links.
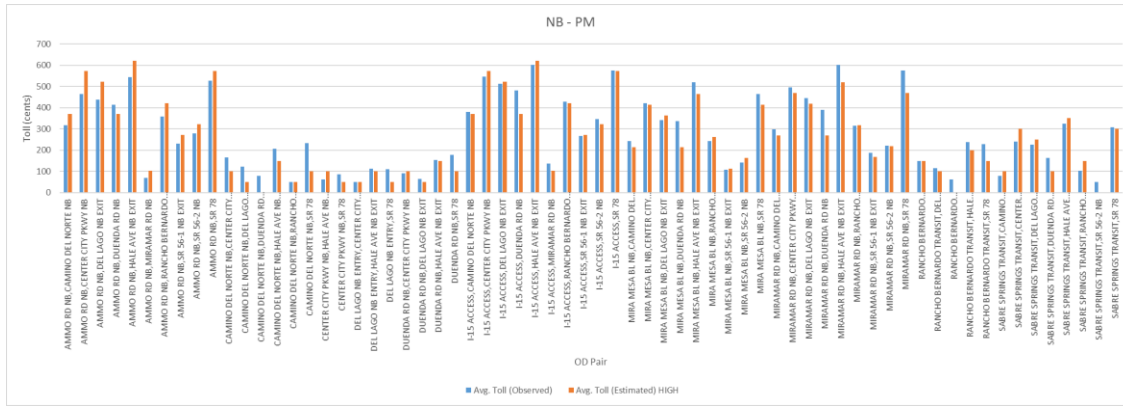
FIGURE 24. NB TOLLS IN PM PERIOD ON I15

The SB direction tolls also showed significant improvement over the old toll costs, however the tolls were still low compared to the observed tolls. A detailed look into the network database revealed that the entry and exit links on the facility were not coded correctly - in some cases entry and exit links did not accurately represent the real-world toll gates on the I15 managed lane facility. These issues were fixed in order to ensure faithful representation of access to the facility and toll costs.

Figure 25 shows the updated entry-exit tolls in the SB direction. (Plots of all time periods are provided in Appendix G)
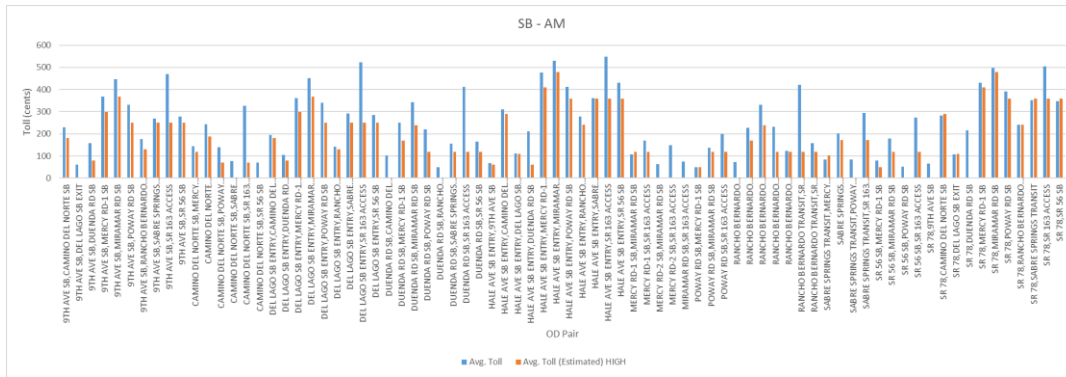
FIGURE 25. SB TOLLS IN PM PERIOD ON I15

The SB tolls showed significant improvement over the original model, however the tolls, even after highway database improvements, are still somewhat low. The lower tolls are due to a skimmed toll path not using the entire toll lane facility from entry gate to exit gate. For several gate pairs, some portion of the toll path consists of general-purpose lane, which results in the skimmed tolls being lower than expected. Those portions of toll paths have higher generalized costs of travel compared to general purpose lanes, thus the path-finder avoids them. The higher generalized costs is a function of a toll that is not offset by a travel time savings based on the value-of-time.

Due to time and budget constraints, this issue was not looked at in further detail but could be investigated as part of additional effort.

6.3 | RUNTIME AND MEMORY

We segment auto skimming and assignment passenger vehicle classes by three value-of-time (VOT) bins, with breakpoints for each group defined by the 33rd, 66th, and 99th percentile of the trip value-of-time distribution ($7.50, $16.00, and $82 respectively). Trip tables are constructed from trip lists based upon the trip's origin and destination zone, time period of departure, chosen mode, and value-of-time. VOT segmentation increases the number of assignment classes from 14 to 30; this results in approximately one additional hour of processing time for a 5000-zone highway assignment per full model iteration (2 processor Intel Xeon E5-2650 v2 @ 2.30GHz) and increases the disk size of output auto skims from 12 Gb to 36 Gb.

TABLE 34. RUN TIME COMPARISON – BEFORE AND AFTER

Period	Iterations			Running Time		
	Original	Revised	Perc Change	Original	Revised	Perc Change
Early AM	3	3	0%	02:06	04:28	113%
AM	28	31	11%	18:58	44:12	133%
Midday	12	14	16%	8:21	20:15	143%
PM	30	29	-3%	18:53	35:53	90%
Evening	3	3	0%	02:08	4:22	105%
Total	76	80	5%	50:26	109:10	116%

Note: The runs times are using TransCAD 6.0 R2 on operating system - Windows 2012 Server 64-bit, and machine - Intel Xeon CPU E5-2650 V3 @2.3 GHz (2 processors) with 256 GB RAM.

7.0   CALIBRATION AND VALIDATION

7.1 | CALIBRATION

The CT-RAMP outputs of the enhanced model were summarized for auto ownership, daily activity pattern, tour mode choice, and trip mode choice. The summaries were compared with similar summaries of the last calibrated SANDAG ABM in April, 2016.

We found little change in auto ownership, activity pattern\tour generation, destination choice or time-of-day choice. However, we did find a need to calibrate the enhanced model to match auto ownership, tour and trip shares better. This was not unexpected given the changes to travel time sensitivities, cost, and reliability introduced in mode choice models. A few rounds of calibration were performed to match auto ownership by, tours by auto sufficiency and tour purpose, and trips by tour mode and trip purpose.

In auto ownership UEC, one new constant adjustment was added. In tour mode choice UEC, three new constant adjustments (by auto sufficiency) were added to 6 tour purposes (work, university, school, maintenance, discretionary, and work-based). The final adjustments added to the tour mode UEC are provided in Appendix B. In trip mode choice UEC, six new constant adjustments (by tour mode) were added to 6 trip purposes (work, university, school, maintenance, discretionary, and subtour).

Summaries of the final calibrated model are presented in Table 35, Table 36, Figure 26, Table 37, and Table 38.

TABLE 35. AUTO OWNERSHIP SUMMARY

	Count		Percentage		
Autos	**Target**	**Model**	**Target**	**Model**	**% Diff**
0	74,558	74,699	6.18%	6.19%	0.2%
1	386,111	385,931	32.00%	31.99%	0.0%
2	481,135	482,586	39.88%	40.00%	0.3%
3	179,562	178,662	14.88%	14.81%	-0.5%
4+	85,160	84,648	7.06%	7.02%	-0.6%
Total	**1,206,526**	**1,206,526**	**100%**	**100%**	

* Target is the last Calibrate ABM (dated April, 2016)

TABLE 36. DAILY ACTIVITY PATTERN (DAP) SUMMARY

PERSONTYPE	Target			Model		
	M	N	H	M	N	H
Full-time worker	87%	8%	5%	87%	8%	5%
Part-time worker	73%	20%	7%	73%	20%	7%
University student	66%	25%	9%	66%	25%	9%
Non-working adult	0%	75%	25%	0%	75%	25%
Non-working senior	0%	73%	27%	0%	73%	27%
Driving age student	91%	4%	5%	91%	4%	5%
Non-driving student	95%	4%	1%	95%	4%	1%
Pre-school	39%	44%	17%	39%	44%	17%
Total	**58%**	**30%**	**11%**	**58%**	**30%**	**12%**

* Target is the last Calibrate ABM (dated April, 2016)

Daily Activity Pattern(DAP) Type Comparison
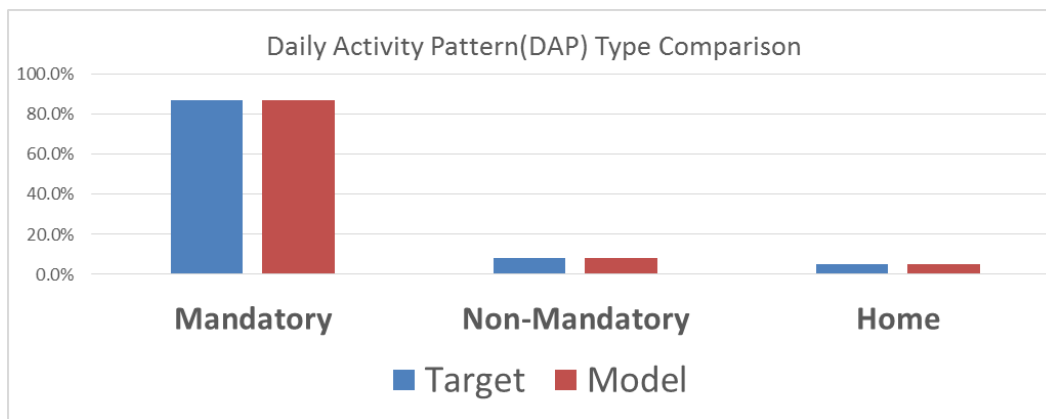
FIGURE 26. DAILY ACTIVITY PATTERN COMPARISON

TABLE 37. TOTAL TOURS BY AUTO OWNERSHIP

Mode	Target				Model			
	0 Auto	Autos < Adults	Autos >= Adults	Total	0 Auto	Autos < Adults	Autos >= Adults	Total
SOV	0.0%	31.1%	46.8%	41.1%	0.0%	30.9%	47.0%	41.2%
HOV2	18.4%	26.3%	20.9%	22.2%	18.5%	26.4%	20.8%	22.2%
HOV3	10.1%	17.2%	23.7%	21.6%	10.0%	17.1%	23.6%	21.4%
WALK	45.6%	15.8%	5.6%	9.7%	45.5%	15.9%	5.6%	9.7%
BIKE	3.2%	1.2%	1.1%	1.2%	3.0%	1.1%	1.0%	1.1%
WLK TRN	17.6%	4.3%	0.3%	1.9%	17.7%	4.2%	0.3%	1.9%
PNR TRN	0.0%	0.7%	0.2%	0.3%	0.0%	0.7%	0.2%	0.3%
KNR TRN	0.5%	0.8%	0.0%	0.2%	0.5%	0.8%	0.0%	0.3%
SCHBUS	4.6%	2.7%	1.4%	1.8%	4.7%	2.8%	1.4%	1.9%
Total	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**

* Target is the last Calibrate ABM (dated April, 2016)

TABLE 38. TOTAL TRIPS BY TOUR MODE

Trip Mode	Target										Model									
										Tour Mode										
	SOV	HOV2	HOV3	WALK	BIKE	WLK TRN	PNR TRN	KNR TRN	SCHBUS	Total	SOV	HOV2	HOV3	WALK	BIKE	WLK TRN	PNR TRN	KNR TRN	SCHBUS	Total
SOV	100.0%	26.8%	10.2%	0.0%	0.0%	0.0%	7.7%	1.1%	0.0%	**51.3%**	100.0%	27.5%	10.6%	0.0%	0.0%	0.0%	7.5%	2.2%	0.0%	**51.4%**
HOV2	0.0%	70.7%	21.0%	0.0%	0.0%	2.8%	4.7%	18.5%	0.0%	**20.4%**	0.0%	70.1%	21.0%	0.0%	0.0%	2.8%	5.1%	17.1%	0.0%	**20.3%**
HOV3	0.0%	0.0%	66.0%	0.0%	0.0%	2.2%	11.6%	4.9%	0.0%	**14.3%**	0.0%	0.0%	65.5%	0.0%	0.0%	2.3%	11.0%	5.1%	0.0%	**14.2%**
WALK	0.0%	2.4%	2.8%	100.0%	0.0%	6.2%	2.1%	5.5%	0.0%	**9.6%**	0.0%	2.5%	2.9%	100.0%	0.0%	5.9%	2.1%	5.7%	0.0%	**9.7%**
BIKE	0.0%	0.0%	0.0%	0.0%	100.0%	0.0%	0.0%	0.0%	0.0%	**1.0%**	0.0%	0.0%	0.0%	0.0%	100.0%	0.0%	0.0%	0.0%	0.0%	**1.0%**
WLK TRN	0.0%	0.0%	0.0%	0.0%	0.0%	88.7%	2.0%	5.7%	0.0%	**1.6%**	0.0%	0.0%	0.0%	0.0%	0.0%	89.1%	2.2%	6.1%	0.0%	**1.6%**
PNR TRN	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	71.8%	5.3%	0.0%	**0.2%**	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	72.2%	11.3%	0.0%	**0.2%**
KNR TRN	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	59.0%	0.0%	**0.1%**	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	52.5%	0.0%	**0.1%**
SCHBUS	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%	**1.4%**	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%	**1.5%**
Total	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	**100.0%**	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	**100.0%**

* Target is the last Calibrate ABM (dated April, 2016)

7.2 | HIGHWAY VALIDATION

Highway flows from the calibrated model matches well with observed counts on the SANDAG network, Figure 27. The R-squared value of the enhanced model (R^2=0.956) is not significantly different than the original model (R^2=0.958). This is perhaps not surprising given that there were only modest changes to link cost with the introduction of travel time reliability. However, more significant changes were observed with respect to toll network validation, as described below.
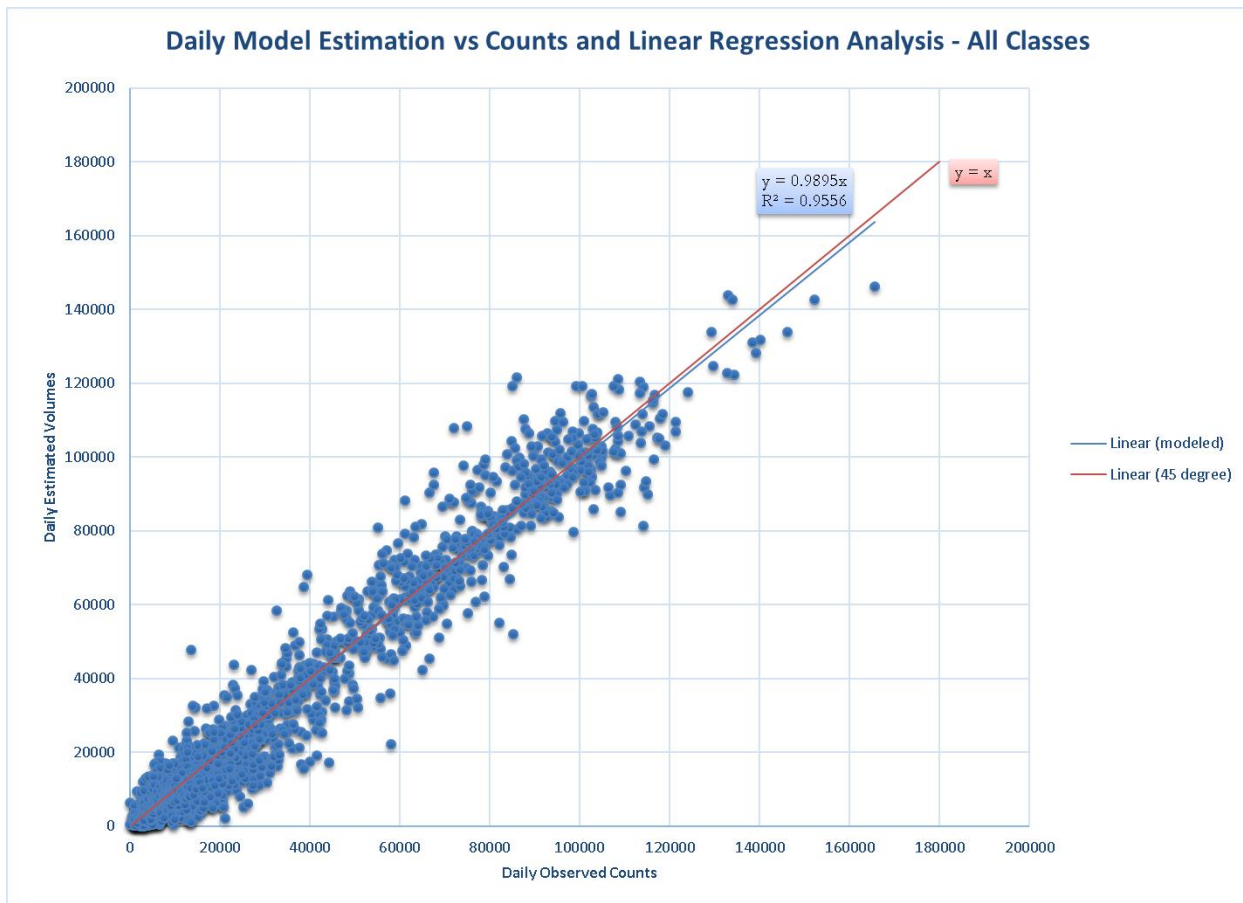
FIGURE 27. HIGHWAY ASSIGNMENT VALIDATION

7.3 | TOLL DEMAND VALIDATION

Toll demand data on the two toll facilities, SR125 toll road and I15 managed lane, in San Diego County (see Figure 4) are validated at link level. The observed data for the toll facilities are described in Section 3.3.

SR125 TOLL ROAD

Estimated toll demand data for the SR125 facility is obtained from the results of final highway assignment of a full ABM run. The highway assignment produces five time period specific binary files containing flows by highway links. To obtain demand comparable to the observed toll demand, demand on highway links corresponding to each consecutive entry and exit points were obtained. The estimated toll demand is first aggregated across all occupancy categories by VOT[8], before calculating the toll demand on a gate-to-gate link. Heavy truck demand is included in the high VOT category for the purposes of plotting the results.

The calculated estimated demand is compared with the observed demand, shown in Figure 28 and Figure 29. Toll demand from the original model (before implementing enhancements) is also included.
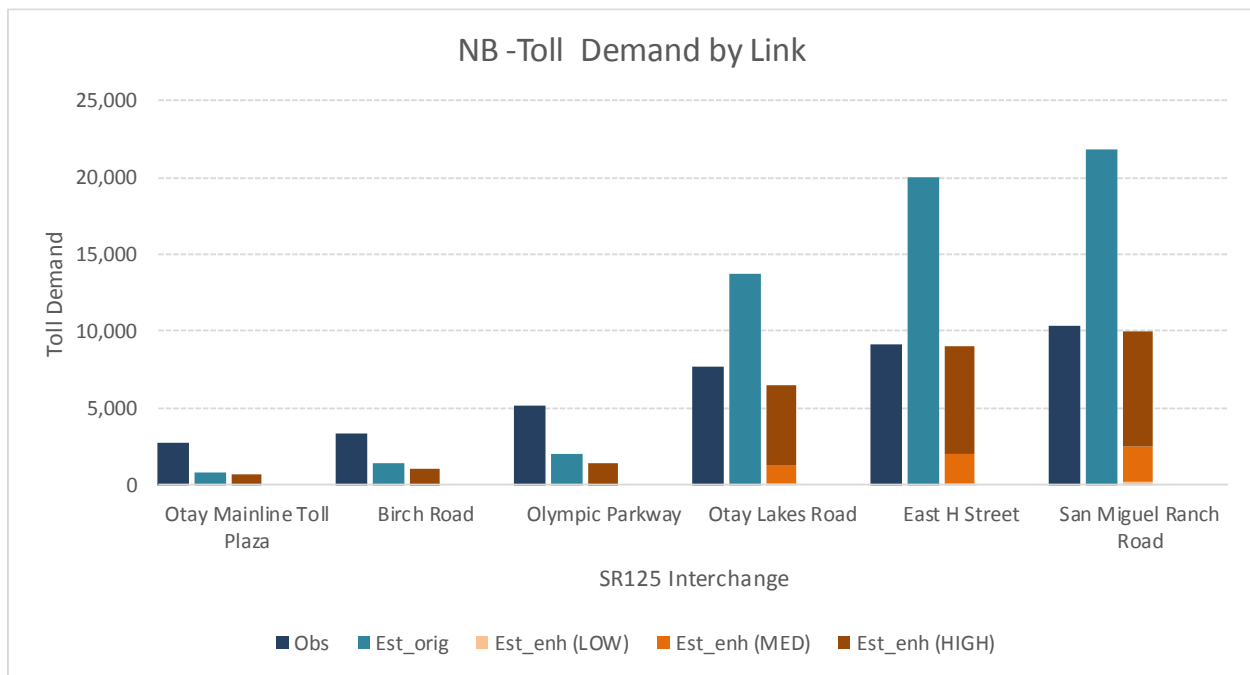
FIGURE 28. NB TOTAL TOLL DEMAND ON THE SR125 – ESTIMATED AND OBSERVED

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[8] For each VOT, following fields are aggregated: "[Dir]_[AutoMode]_FLOW_PAY_[VOT]". Where, Dir = AB, BA; AutoMode = SOV, SR2, SR3; and VOT=LOW, MED, HIGH. In addition, HIGH VOT category includes truck toll demand from the following fields: "AB/BA_Flow_lhdt", "AB/BA_Flow_mhdt", and "AB/BA_Flow_hhdt".
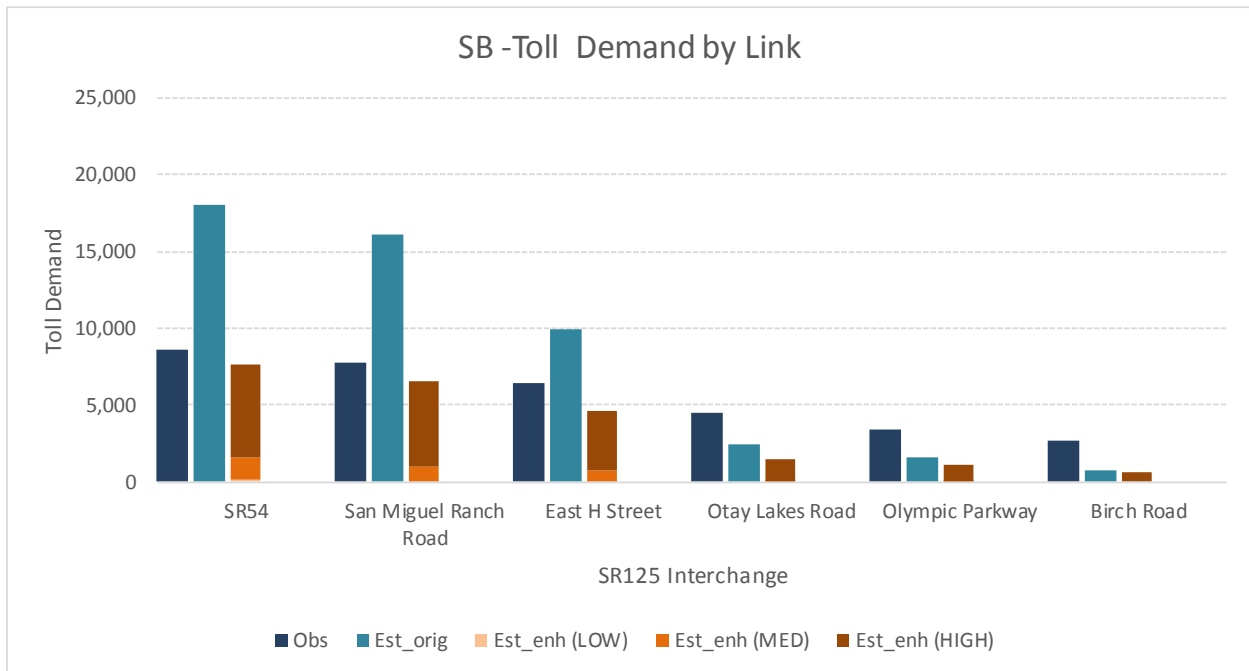
FIGURE 29. SB TOTAL TOLL DEMAND ON THE SR125– ESTIMATED AND OBSERVED

The original model estimated very high toll demand for north end of the facility (Otay Lakes Road to San Miguel Ranch Road) and lower near the border (Otay Mainline Toll Plaza to Olympic Parkway). The enhanced model improved the demand on the north end of the facility.

Irrespective of travel direction, the estimated demand is lower compared to the observed toll demand. The south end of the toll facility (towards the Mexico border) between Olympic Parkway and the Otay Mainline Toll Plaza is significantly lower than the respective observed toll demand in either direction. This could be an indication of lower cross-border model demand than actual, or too few origin-destination pairs finding a toll path for the southern end of the corridor due to lack of travel time savings.

A similar problem was observed in the original model results as well. The revised model increases the demand at the southern end of the corridor, but not enough to make up for the difference compared to observed demand. It should be noted that the original model included a discounted cost function for SR-125 to account for reliability of the toll facility. The new model eliminates this 'fudge-factor' since reliability is directly incorporated in the volume-delay function. So, it can be stated that the new model is more sensitive to network inputs and improves the match to observed data but could still be improved.

VOT categories enables us to see toll demand corresponding to a VOT category. Because the facility offers little time savings compared to alternative free routes in the model, most of the demand is in the high VOT category. In fact, a path on SR-125 is not found for low and medium VOT categories for three out of six interchanges.. However, it is clear that the overall problem is not with the value-of-times used in the model, but rather the overall demand, since even the high VOT category has very low demand at the southern end of the corridor.

I15 MANAGED LANE

The estimated data were obtained from the outputs of final highway assignment[9] and compared to observed demand described in Section 3.0.

We noticed that estimated toll demand was between three and four times higher than the observed demand in both the original model and the enhanced model. We note that unlike SR-125, I-15 is a dynamically-priced high-occupancy toll lane that requires a transponder to use for single-occupant vehicles (there is no cash option). The original model included a transponder choice component, but this component was not active and did not restrict the use of I-15 despite the transponder requirement. Therefore, we modified the model to restrict the availability of the toll-eligible drive-alone mode in tour and trip mode choice based upon the availability of a transponder in the household as predicted by the transponder ownership model. A list of all changes made to enable the transponder choice model are provided in Appendix C.

The model with transponder choice model enabled produced toll demand that matched the observed toll demand much closer on the I15 toll managed lane facility. The comparison of the estimated and observed demand on the facility is shown in Figure 30 and Figure 31.
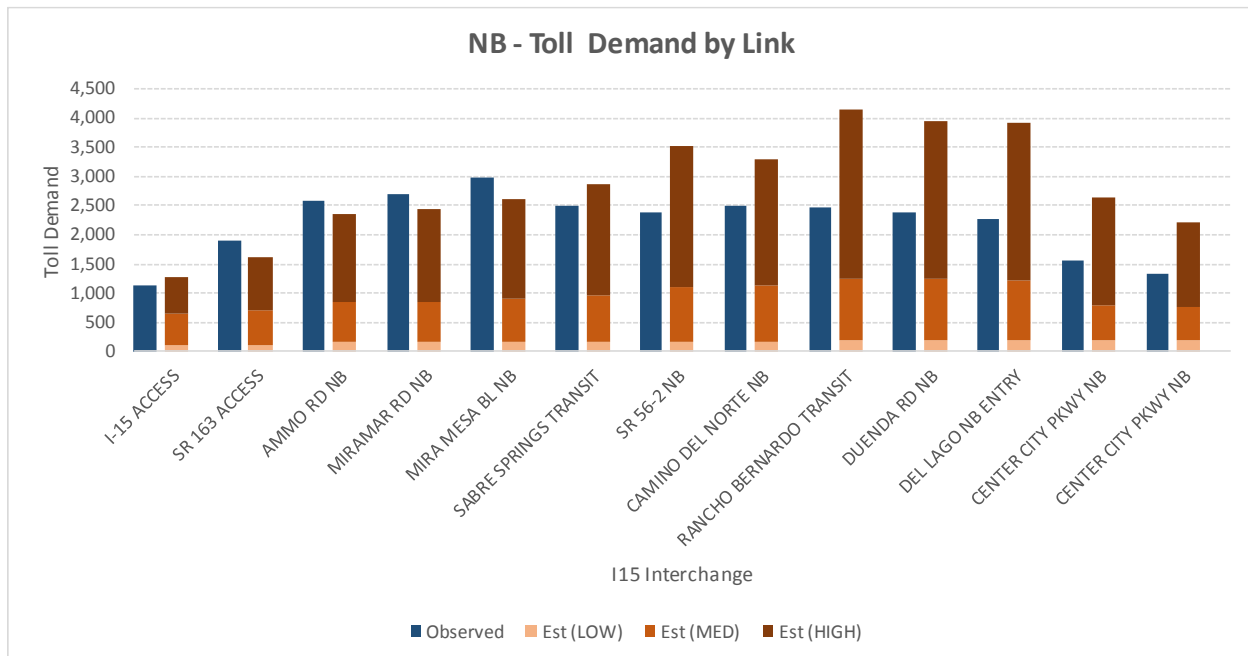
FIGURE 30. NB TOLL DEMAND ON I15 – OBSERVED AND ESTIMATED

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[9] The data included SOV toll flows ("AB/BA_Flow_SOV_PAY_[VOT]") and extracted using link ids corresponding to the gate pairs. The following are the related flow fields: ("[Dir]_Flow_SOV_PAY_[VOT]"; where Dir = AB, BA; and VOT = LOW, MED, HIGH.

SB - Toll Demand by Link

(Chart: x-axis "I15 Interchange"; y-axis "Toll Demand" ranging 0 to 4,500. Series: Observed, Est (LOW), Est (MED), Est (HIGH). Interchanges from left to right: SR 78, HALE AVE SB ENTRY, 9TH AVE SB, DEL LAGO SB ENTRY, DUENDA RD SB, RANCHO BERNARDO TRANSIT, CAMINO DEL NORTE SB, SABRE SPRINGS TRANSIT, SR 56 SB, POWAY RD SB, MERCY RD-1 SB, MERCY RD-2 SB, MIRAMAR RD SB.)
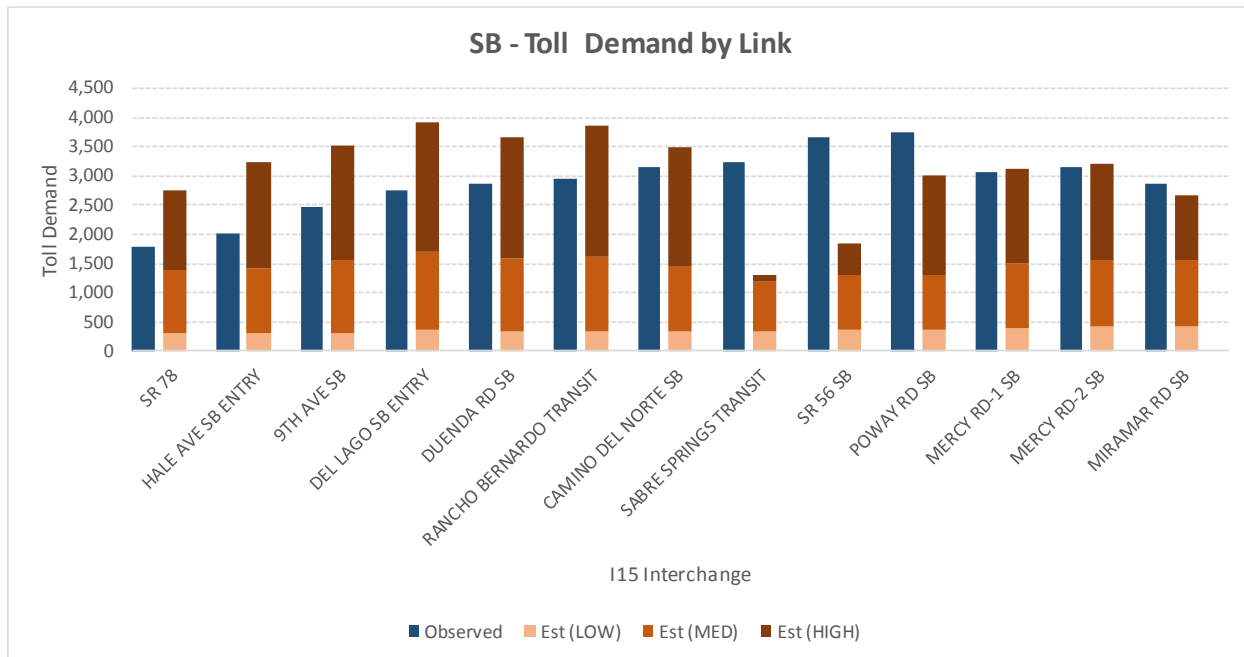
FIGURE 31. SB TOLL DEMAND ON I15 – OBSERVED AND ESTIMATED

Only Sabre Springs Transit and SR 56 SB interchanges have significantly lower demand than observed in the SB direction. The NB direction is low at the south end (I15 Access to Sabre Spring Transit) and high on a few gate pairs (Rancho Bernado Transit, Duenda Rd NB, Del Lago Entry) at the north end of the managed lane facility. However, overall the demand profile matches observed very well.

8.0   SENSITIVITY TESTS

The presence of two existing toll facilities in the San Diego region provides a unique opportunity to perform realistic sensitivity tests of the model system.

The following two tests were designed to assess the toll sensitivity of the enhanced model:

- Test 1 – effect on toll demand with half of the original toll
- Test 2 – effect on toll demand with double of the original toll

To setup a sensitivity test, the toll fields ITOLL2_[period] were recalculated by applying a factor (0.5 for half toll and 2 for double toll) to the original values. For example, following GISDK code is used to perform the calculations for test 1.

```
  // for sensitivity test - half toll
  tollfactor = "0.5*"
for i=1 to tollfld.length do
    Opts = null
    Opts.Input.[View Set] = {db_link_lyr, link_lyr}
    Opts.Input.[Dataview Set] = {db_link_lyr, link_lyr}
    Opts.Global.Fields = tollfld[i]
    Opts.Global.Method = "Formula"
    Opts.Global.Parameter = {tollfactor+tollfld[i][1]}
    ok = RunMacro("TCB Run Operation", 1, "Fill Dataview", Opts)
    if !ok then goto quit
end
```

FIGURE 32. SENSITIVITY TEST 1 SETUP

8.1 | TEST 1 - HALF TOLL

As expected, lowering toll (half) on the toll facilities resulted in more demand. Reduction in toll increased attractiveness (utility) of the toll facilities, thus inducing more vehicle trips.

SR 125 TOLL ROAD

SR125 toll demand comparisons for consecutive gate pairs by direction are shown in Figure 33 and Figure 34, and in Table 39 and Table 40. Elasticities are in the range of -0.95 to -1.16 in the NB direction and -1.24 to -1.56 in the SB direction. Note that the reduction in tolls induces some additional low and medium VOT travelers to use certain interchange pairs that are only used by medium and high VOT travelers in the base alternative.

FIGURE 33. SENSITIVITY TEST 1 – NB TOLL DEMAND BY VOT ON SR125

FIGURE 34. SENSITIVITY TEST 1 – SB TOLL DEMAND BY VOT ON SR125

TABLE 39. SENSITIVITY TEST 1 – NB TOTAL TOLL DEMAND ON SR125

Plaza 1	Plaza 2	Base	Test 1	Diff (%)	Elasticity
Otay Mainline Toll Plaza	Birch Road	643	995	55%	-1.10
Birch Road	Olympic Parkway	1,038	1,529	47%	-0.95
Olympic Parkway	Otay Lakes Road	1,397	2,073	48%	-0.97
Otay Lakes Road	East H Street	5,867	9,109	55%	-1.11
East H Street	San Miguel Ranch Road	8,010	12,642	58%	-1.16
San Miguel Ranch Road	SR54	8,889	13,936	57%	-1.14

TABLE 40. SENSITIVITY TEST 1 – SB TOTAL TOLL DEMAND ON SR125

Plaza 1	Plaza 2	Base	Test 1	Diff (%)	Elasticity
SR54	San Miguel Ranch Road	6,612	11,308	71%	-1.42
San Miguel Ranch Road	East H Street	5,699	10,149	78%	-1.56
East H Street	Otay Lakes Road	4,013	6,777	69%	-1.38
Otay Lakes Road	Olympic Parkway	1,277	2,241	75%	-1.51
Olympic Parkway	Birch Road	925	1,608	74%	-1.48
Birch Road	Otay Mainline Toll Plaza	551	892	62%	-1.24

I15 MANAGED LANE

Figure 35, Figure 36, Table 41 and Table 42 show toll demand comparisons by direction on I15 toll lane facility. Elasticities are in the range of -1.29 to -5.71 in the NB direction and -0.55 to -1.93 in the SB direction. Generally, the demand in the NB direction increases more than the SB direction; this may be due to more travel time savings per unit of cost in this direction. Similar to the SR125 toll road, a higher VOT category sees a higher increase in vehicle trips on the I15 toll facility.
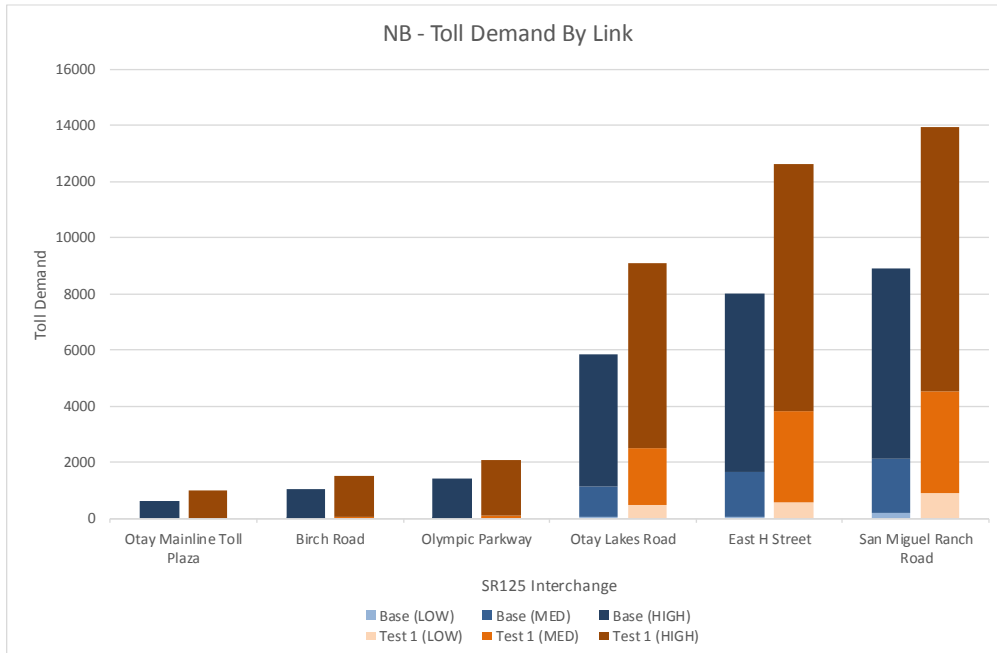

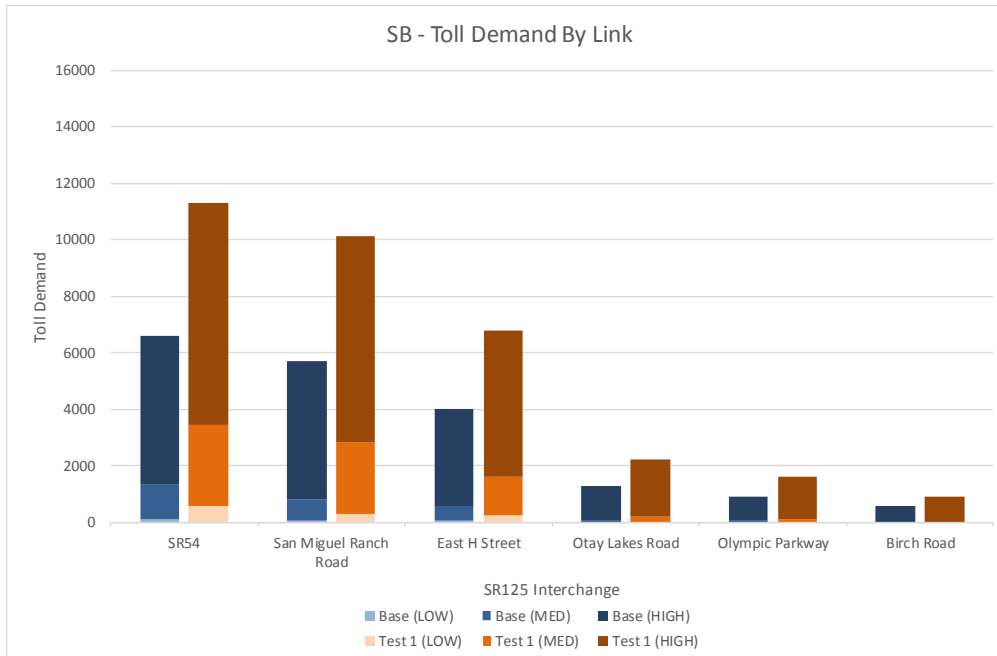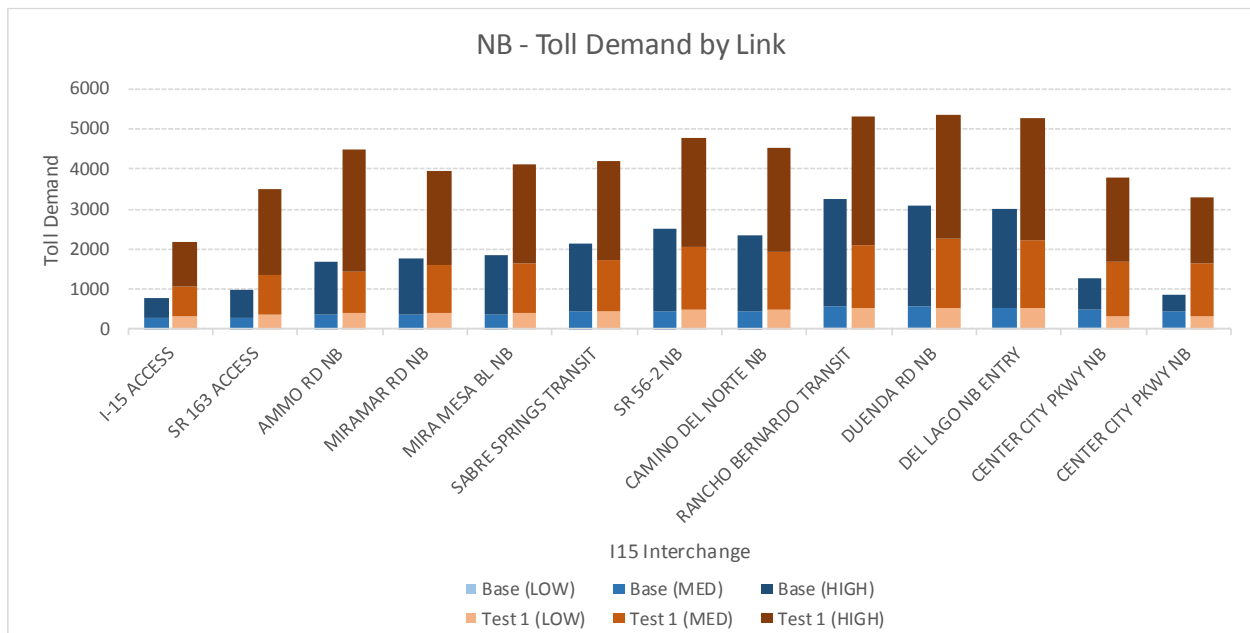**FIGURE 35. SENSITIVITY TEST 1 - NB TOLL DEMAND BY VOT ON I15**
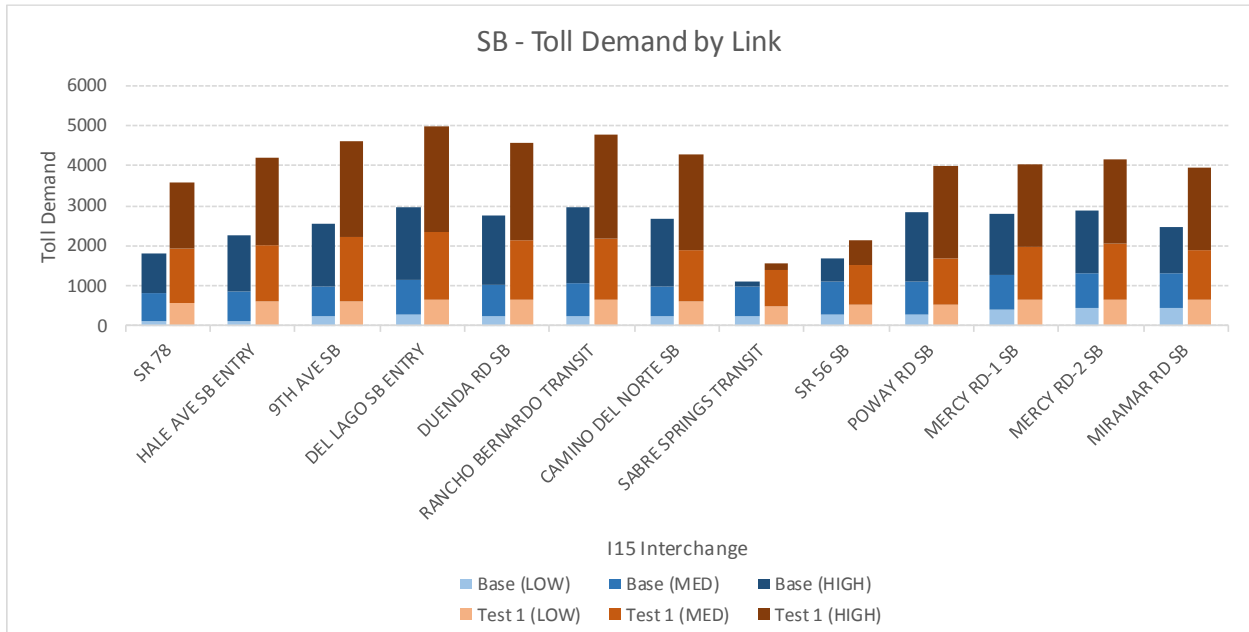
FIGURE 36. SENSITIVITY TEST 1 - SB TOLL DEMAND BY VOT ON I15

TABLE 41. SENSITIVITY TEST 1 – NB TOTAL TOLL DEMAND ON I15

Plaza 1	Plaza 2	Base	Test 1	Diff (%)	Elasticity
I-15 Access	Miramar Rd NB	778	2,201	183%	-3.66
SR 163 Access	Miramar Rd NB	985	3,501	256%	-5.11
Ammo Rd NB	Miramar Rd NB	1,672	4,503	169%	-3.38
Miramar Rd NB	SR 56-1 NB Exit	1,770	3,944	123%	-2.46
Mira Mesa Bl NB	SR 56-1 NB Exit	1,867	4,109	120%	-2.40
Sabre Springs Transit	SR 56-2 NB	2,122	4,211	98%	-1.97
SR 56-2 NB	Camino Del Norte NB	2,530	4,761	88%	-1.76
Camino Del Norte NB	Rancho Bernardo Transit	2,360	4,525	92%	-1.84
Rancho Bernardo Transit	Duenda Rd NB	3,241	5,323	64%	-1.29
Duenda Rd NB	Del Lago NB Exit	3,073	5,345	74%	-1.48
Del Lago NB Entry	Center City Pkwy NB	3,003	5,275	76%	-1.51
Center City Pkwy NB	Hale Ave NB Exit	1,259	3,791	201%	-4.02
Center City Pkwy NB	SR 78	855	3,296	286%	-5.71

TABLE 42 SENSITIVITY TEST 1 – SB TOTAL TOLL DEMAND ON I15

Plaza 1	Plaza 2	Base	Test 1	Diff (%)	Elasticity
SR 78	9th Ave SB	1,820	3,576	97%	-1.93
Hale Ave SB Entry	9th Ave SB	2,268	4,186	85%	-1.69
9th Ave SB	Del Lago SB Exit	2,547	4,628	82%	-1.63
Del Lago SB Entry	Duenda Rd SB	2,956	4,992	69%	-1.38
Duenda Rd SB	Rancho Bernardo Transit	2,737	4,584	67%	-1.35
Rancho Bernardo Transit	Camino Del Norte SB	2,947	4,792	63%	-1.25
Camino Del Norte SB	SR 56 SB	2,664	4,297	61%	-1.23
Sabre Springs Transit	SR 56 SB	1,090	1,541	41%	-0.83
SR 56 SB	Poway Rd SB	1,690	2,157	28%	-0.55
Poway Rd SB	Mercy Rd-1 SB	2,834	4,002	41%	-0.82
Mercy Rd-1 SB	Miramar Rd SB	2,806	4,022	43%	-0.87
Mercy Rd-2 SB	Miramar Rd SB	2,894	4,144	43%	-0.86
Miramar Rd SB	SR 163 Access	2,464	3,958	61%	-1.21

8.2 | TEST 2 - DOUBLE TOLL

Charging higher tolls (double) on the toll facilities caused reduction in toll demand, which is intuitive as more tolls increase cost of travel and decrease the utility of choosing a toll facility, thus fewer vehicle enter the facility.

SR 125 TOLL ROAD

Figure 37, Figure 38, Table 43, and Table 44 show toll demand comparisons on the SR125 toll facility. With increase (100%) in tolls, a higher VOT category sees a bigger decrease in demand for the facility. Now, the facility is mostly used by the high VOT demand with no low VOT demand. Elasticities are in the range of -0.40 to -0.57 for NB and -0.49 to -0.51 in SB

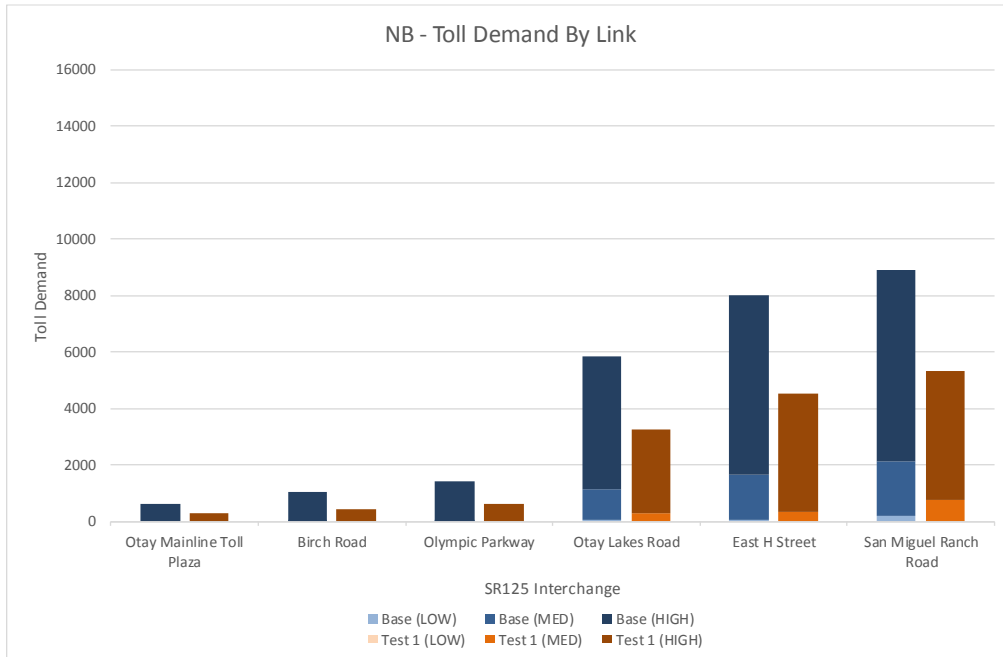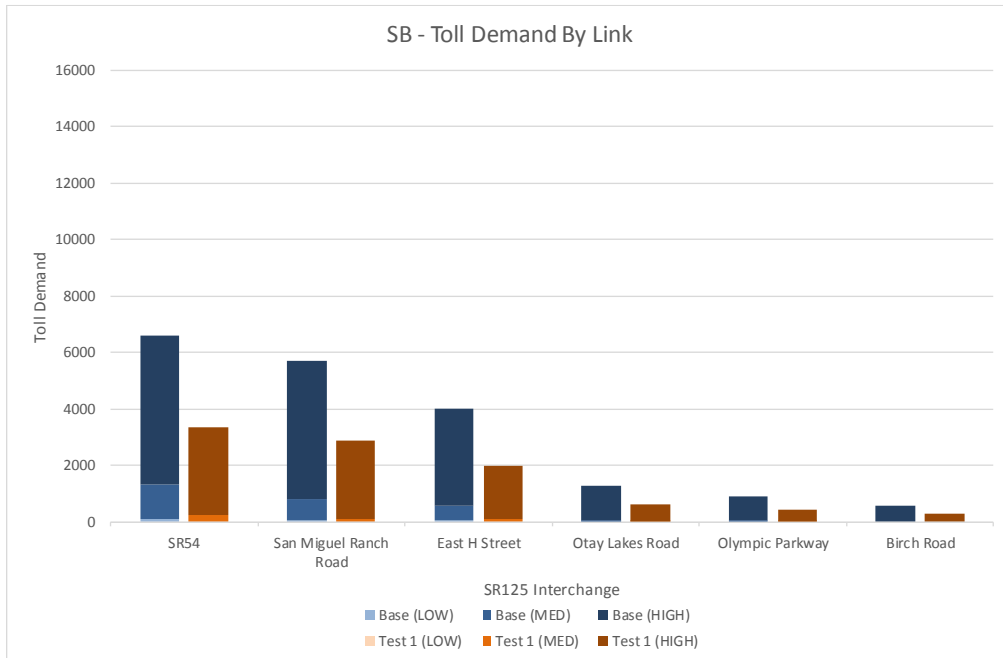**FIGURE 37. SENSITIVITY TEST 2 – NB TOLL DEMAND ON SR125**

FIGURE 38. SENSITIVITY TEST 2 – SB TOLL DEMAND ON SR125

TABLE 43. SENSITIVITY TEST 2 – NB TOLL DEMAND ON SR125

Plaza 1	Plaza 2	Base	Test 2	Diff (%)	Elasticity
Otay Mainline Toll Plaza	Birch Road	643	278	-57%	-0.57
Birch Road	Olympic Parkway	1038	449	-57%	-0.57
Olympic Parkway	Otay Lakes Road	1397	614	-56%	-0.56
Otay Lakes Road	East H Street	5867	3273	-44%	-0.44
East H Street	San Miguel Ranch Road	8010	4522	-44%	-0.44
San Miguel Ranch Road	SR54	8889	5315	-40%	-0.40

TABLE 44. SENSITIVITY TEST 2 – SB TOLL DEMAND ON SR125

Plaza 1	Plaza 2	Base	Test 2	Diff (%)	Elasticity
SR54	San Miguel Ranch Road	6612	3342	-49%	-0.49
San Miguel Ranch Road	East H Street	5699	2878	-50%	-0.50
East H Street	Otay Lakes Road	4013	1992	-50%	-0.50
Otay Lakes Road	Olympic Parkway	1277	620	-51%	-0.51
Olympic Parkway	Birch Road	925	453	-51%	-0.51
Birch Road	Otay Mainline Toll Plaza	551	274	-50%	-0.50

I15 MANAGED LANE

Comparisons of directional toll demand on I15 toll facility are presented in Figure 39, Figure 40, Table 45, and Table 46. Similar to the impact of lower tolls (sensitivity test 1), the NB direction experienced more decrease in I15 toll demand than the SB direction.

Surprisingly, the segment 'Sabre Spring Transit – SR 56 SB' experienced a little increase in the total toll demand. Another segment 'SR56 SB – Poway Rd SB' saw almost the same demand as in the base year. For both segments, the higher toll test estimates reduced the low and the medium VOT demand. However, increase in the high VOT demand compensated for the reduction in the total demand. For the two segments, the base year scenario itself estimates substantially lower demand compared to the observed, Figure 31. This suggests that parallel general purpose (GP) lanes may be operating at a similar level of service as of the toll lanes, thus not providing enough travel time savings by paying tolls. With increase in tolls, some of the low and the medium VOT toll demand would move to the GP lanes, which would worsen travel times on the lanes. Due to their higher sensitivity to travel times, the high VOT demand would shift from the GP lanes to the toll lanes as for them gain in travel times would be higher than the increase in toll costs. This suggests that parallel general purpose (GP) lanes may be operating at a similar level of service as of the toll lanes, thus not providing enough travel time savings by paying tolls. With increase in tolls, some of the low and the medium VOT toll demand would move to the GP lanes, which would worsen travel times on the lanes. Due to their higher sensitivity to travel times, the high VOT demand would shift from the GP lanes to the toll lanes as for them gain in travel times would be higher than the increase in toll costs.

Elasticities are in the range of -0.48 to 0.27 for NB and -0.41 to 0.06 in SB.
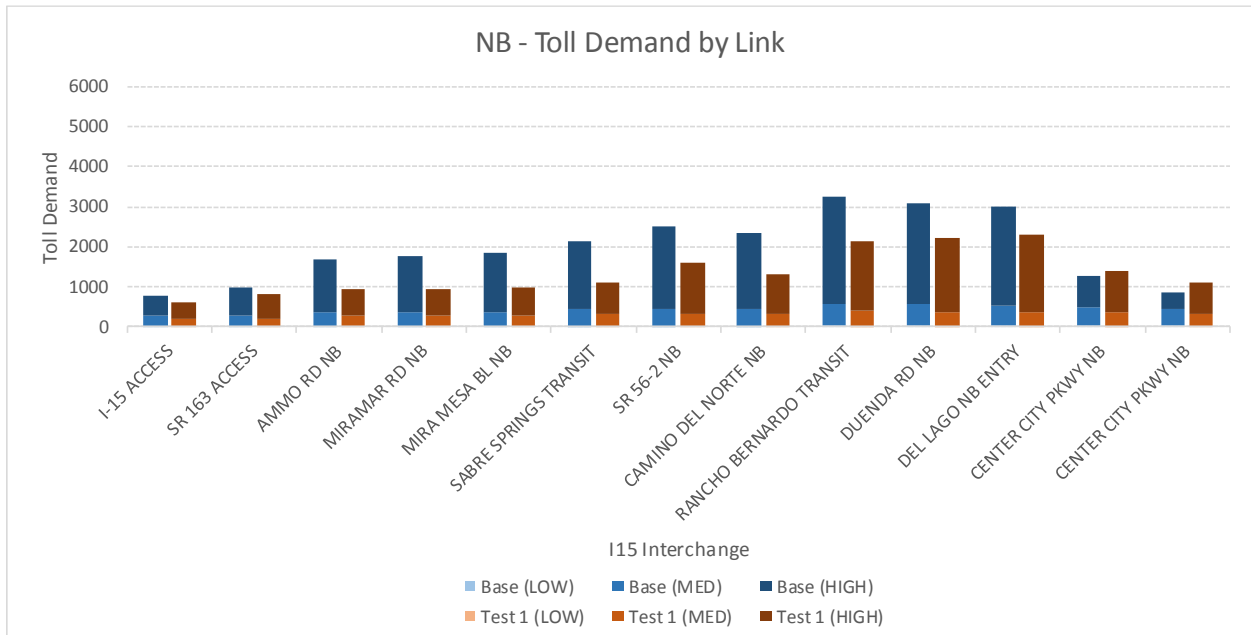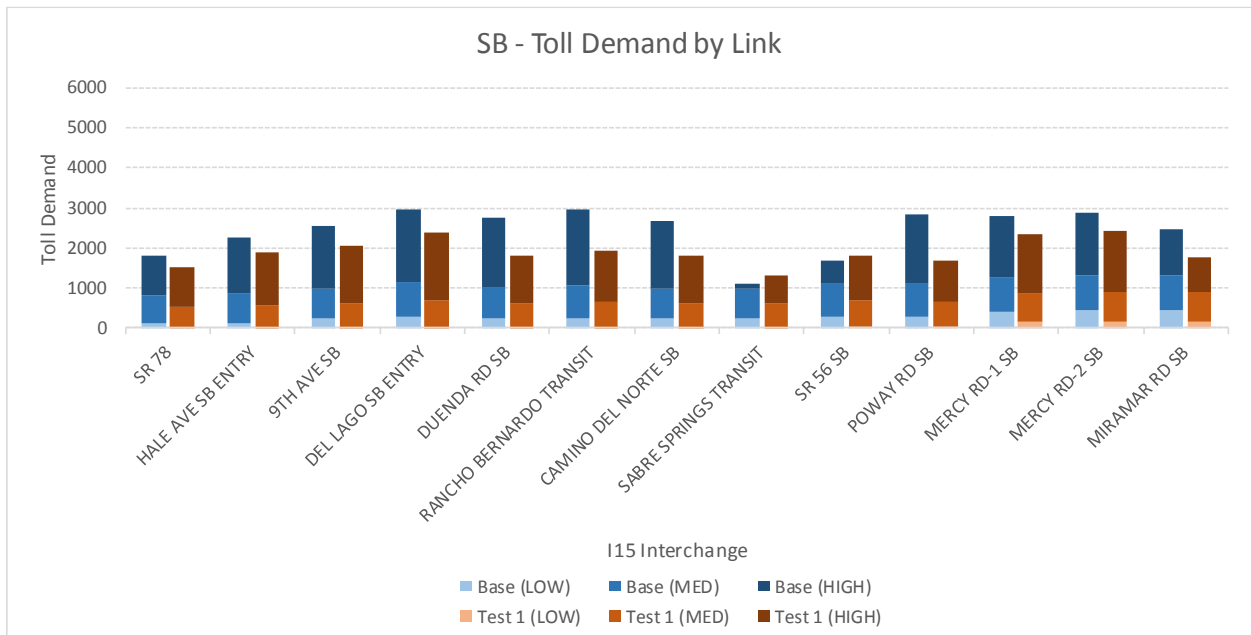
FIGURE 39**. SENSITIVITY TEST 2 - NB TOLL DEMAND ON I15**

FIGURE 40. SENSITIVITY TEST 2 - SB TOLL DEMAND ON I15

TABLE 45. SENSITIVITY TEST 2 – NB TOLL DEMAND ON I15

Plaza 1	Plaza 2	Base	Test 2	Diff (%)	Elasticity
I-15 Access	Miramar Rd NB	778	615	-21%	-0.21
SR 163 Access	Miramar Rd NB	985	813	-17%	-0.17
Ammo Rd NB	Miramar Rd NB	1,672	923	-45%	-0.45
Miramar Rd NB	SR 56-1 NB Exit	1,770	931	-47%	-0.47
Mira Mesa Bl NB	SR 56-1 NB Exit	1,867	975	-48%	-0.48
Sabre Springs Transit	SR 56-2 NB	2,122	1,098	-48%	-0.48
SR 56-2 NB	Camino Del Norte NB	2,530	1,603	-37%	-0.37
Camino Del Norte NB	Rancho Bernardo Transit	2,360	1,326	-44%	-0.44
Rancho Bernardo Transit	Duenda Rd NB	3,241	2,135	-34%	-0.34
Duenda Rd NB	Del Lago NB Exit	3,073	2,238	-27%	-0.27
Del Lago NB Entry	Center City Pkwy NB	3,003	2,288	-24%	-0.24
Center City Pkwy NB	Hale Ave NB Exit	1,259	1,380	10%	0.10
Center City Pkwy NB	SR 78	855	1,088	27%	0.27

TABLE 46. SENSITIVITY TEST 2 – SB TOLL DEMAND ON I15

Plaza 1	Plaza 2	Base	Test 2	Diff (%)	Elasticity
SR 78	9th Ave SB	1,820	1,531	-16%	-0.16
Hale Ave SB Entry	9th Ave SB	2,268	1,887	-17%	-0.17
9th Ave SB	Del Lago SB Exit	2,547	2,041	-20%	-0.20
Del Lago SB Entry	Duenda Rd SB	2,956	2,402	-19%	-0.19
Duenda Rd SB	Rancho Bernardo Transit	2,737	1,810	-34%	-0.34
Rancho Bernardo Transit	Camino Del Norte SB	2,947	1,952	-34%	-0.34
Camino Del Norte SB	SR 56 SB	2,664	1,813	-32%	-0.32
Sabre Springs Transit	SR 56 SB	1,090	1,325	22%	0.22
SR 56 SB	Poway Rd SB	1,690	1,795	6%	0.06
Poway Rd SB	Mercy Rd-1 SB	2,834	1,674	-41%	-0.41
Mercy Rd-1 SB	Miramar Rd SB	2,806	2,363	-16%	-0.16
Mercy Rd-2 SB	Miramar Rd SB	2,894	2,416	-17%	-0.17
Miramar Rd SB	SR 163 Access	2,464	1,761	-29%	-0.29

8.3 | SUMMARY

The toll facilities responded to toll cost changes as expected. A decrease in tolls induced more demand and an increase in tolls resulted in lower demand on the facilities. A comparison of demand by VOT categories provides insight into how toll prices affected demand in different income segments.

The toll reduction scenario produced higher range of elasticities compared to the toll increase scenario, suggesting a somewhat non-continuous response surface for toll cost. This response may be logical given the shape of the VOT curve, which is right-skewed; a reduction in tolls may induce the higher proportion of travelers with a VOT around the mean to use toll facilities. Reducing tolls by half (-50%) resulted in elasticities of -0.95 to -1.56 on the SR 125 toll facility and -0.55 to -5.71 on the I15 toll facility. Increasing tolls by 100% resulted in elasticities of -0.40 to -0.57 on the SR125 toll facility and -0.48 to 0.27 on the I15 toll facility.

The elasticities resulting from decreasing tolls (sensitivity test 1) are a bit higher than average elasticities we find in the literature, while elasticities resulted from increasing tolls (sensitivity test 2) are consistent with other studies. Litman (2003) reported auto demand elasticity of -0.63 for congestion pricing to enter downtown London during weekdays. The toll roads in Spain observed car short term elasticities in the range of -0.21 to -0.83 (Matas and Raymond, 2003). Holguin-Veras, Ozbay and de Cerreno (2005) analyzed demand data (2000-2001) for the six interstate bridges and tunnels to link New Jersey with New York City and calculated car short-term elasticities for E-ZPass tolls in the range of -0.31 to -1.97 during weekdays. A case study of two toll bridges in Lee County, Florida analyzed demand data in shoulders of peak periods and observed elasticities ranging from -0.05 to -0.36 (Litman, 2013). In 2000, New Jersey Turnpike Authority increased cash tolls for cars by 20% for travel during weekday peak hours and saw an increase of about 4%-6% in demand during peak periods, suggesting elasticities of -0.2 to -0.3 (Litman, 2013).

SUMMARY AND CONCLUSIONS

This project has successfully demonstrated that it is possible to increase model sensitivity to pricing and reliability in activity-based travel demand models, through incorporation of recommendations from SHRP C04 and L03 and L04 research. Moreover, we demonstrate that understanding local conditions are essential to accurately modeling toll demand. For example, the faithful coding of entry-exit points, toll costs, and toll road restrictions (such as Fastrack) are required. Finally, we believe significant practically-oriented research challenges remain, particularly with respect to measuring reliability and incorporating it into travel demand models.

We summarize the tasks completed and major findings and recommendations of each task below:

1) **SHRP C04 implementation:** We successfully implemented the SHRP C04 auto utility equation in the SANDAG activity-based travel demand model. This includes distributed travel time sensitivity, continuous cost sensitivity based on household income, cost-sharing according to auto occupancy, and travel time variability. The changes resulted in minimal increase in model runtime (less than four hours across three full model feedback implementations). However, there were significant memory implications due to the increase in auto skims. The model now requires a PC with over 200 GB of RAM to run monolithically, due to the introduction of three value-of-time bins. Obviously the RAM requirements are also a function of number of auto modes, time periods, and zones, so these results will vary between regions. We find that the inclusion of VOT bins improves the estimation of demand on SR-125, and provides additional data for the analysis of toll alternatives.

2) **Travel time variability:** We acquired, processed, and analyzed an INRIX travel time dataset for San Diego county, and used it to estimate relationships between network characteristics and travel time variability. We successfully implemented those equations in volume-delay functions and skim travel time variability. The equations incorporate more explanatory variables than previous work has included, and are based on local conditions. We find the resulting relationship between travel time and travel time variability to be reasonable across the range of facility types and travel times. We also find that the incorporation of reliability does not significantly affect overall assignment validation results. We find a key advantage of including reliability explicitly in that we are able to eliminate an adjustment factor previously employed on SR-125 to better match toll demand on that specific facility. However, we find that static cross-sectional estimation of travel time reliability, and the method used to incorporate reliability in assignment falls short of what is needed for truly robust measurements of variability. It assumes independence of estimates of variance, ignoring correlations in travel time across network links and through time. For future research, we recommend analysis of observed travel time variability using a time-dependent path-finding algorithm so that link dependence can be measured. We further recommend further research into practical static equilibrium path-finding algorithms that are capable of incorporating travel time variability in a theoretically consistent and computationally efficient manner.

3) **Observed toll data analysis and toll demand refinement:** We obtained observed toll demand and price data for two toll facilities in San Diego county (SR-125 and I-15) for 2012. We processed the data and used a linear optimization method to calculate toll costs by facility, interchange, and time of day. Including the revised toll costs in skimming and assignment improves model results. We also

find that the inclusion of a transponder ownership model is essential to replicate demand in the I-15 corridor. We find that the revised, enhanced model is better able to match observed demand than the previous model.

4) ***Sensitivity tests:*** We perform two sensitivity tests, where base-year tolls are decreased by 50% and increased by 100%, to determine model elasticities with respect to cost. We find that the halving of tolls results in higher elasticities with respect to toll cost the doubling of tolls. We find the elasticity values generally in the ranges reported in the literature.

We believe that this research is a valuable contribution to the modeling community. This research is particularly applicable to the large number of metropolitan regions that have developed or are developing activity-based travel demand models, and who are interested in analyzing priced highway lanes as a tool to manage congestion, increase mobility options, and raise revenue for transport investments. Many of the recommendations and enhancements in this report are ready for implementation and do not require large investments in hardware or software, and do not increase runtime beyond reasonable time-frames for most regional analysis.

9.0 ACKNOWLEDGEMENT

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APPENDIX A.   TMC SEGMENT

A TMC code consists of nine characters that define a unique segment and direction of roadway in North America.
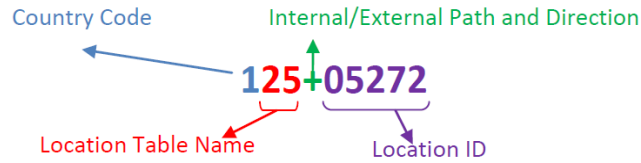
Figure. Interpretation of a TMC segment (Source: INRIX_Dev_Guide.pdf)

Table. TMC segment naming convention

Digit Location	Description	Example	Possible (range) values
Digit 1	Country Code	1	"1" for US, and "C" for Canada
Digit 2-3	Location table name	25	1-35
Digit 4	Internal/external path and direction	+	"+", "-", "P","N"
Digit 5-9	Location id	05272	

The first digit (Digit 1) refers to country code. Next two digits (Digit 2-3) correspond to the location table name. Thirty five distinct tables, as shown in Figure 1, are assigned to North America.

Figure. Country Codes (Source: INRIX_Dev_Guide.pdf)

Next digit (Digit 4) is for direction of travel and if the TMC segment is "internal" or "external". The digit takes four possible values: "+", "-", "P","N". Examples of Internal and external TMC segments are presented in Figure xx.
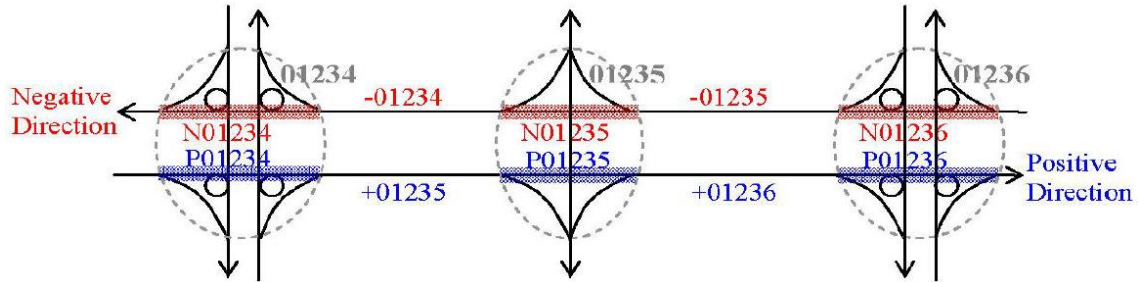
Figure. TMC Segment direction of travel and internal/external

In most situations, the below are what they mean:

- "P" – Northbound or Westbound, internal segments
- "N" – Southbound or Eastbound, internal segments
- "+" – Northbound or Westbound, external segments
- "-" – Southbound or Eastbound, external segments

The last 5 digits (Digit 5-9) identifies the specific location id in the location table that is toes to a specific interchange, intersection, boundary, or decision point.

APPENDIX B.   TOUR MODE CHOICE UEC ADJUSTMENTS

TABLE 47. TOUR MODE CHOICE UEC ADJUSTMENTS FOR WORK PURPOSE

Mode	0 Auto	Autos < Adults	Autos >= Adults
SOV	-	-*	-*
HOV2	-*	0.072	0.043
HOV3	0.050	0.088	0.044
WALK	-0.477	-0.294	-0.526
BIKE	-0.513	-0.067	-0.404
WLK TRN	-0.392	-0.571	-0.605
PNR TRN	-	0.175	0.136
KNR TRN	0.078	0.152	-0.033
SCHBUS	-	-	-

* reference category

TABLE 48. TOUR MODE CHOICE UEC ADJUSTMENTS FOR COLLEGE PURPOSE

Mode	0 Auto	Autos < Adults	Autos >= Adults
SOV	-	-*	-*
HOV2	-*	0.138	0.094
HOV3	0.000	0.139	0.116
WALK	-0.093	-0.440	-0.652
BIKE	-1.434	-0.277	-0.550
WLK TRN	0.393	-0.493	-0.190
PNR TRN	-	0.259	0.431
KNR TRN	1.138	0.099	0.221
SCHBUS	-	-	-

* reference category

TABLE 49. TOUR MODE CHOICE UEC ADJUSTMENTS FOR SCHOOL PURPOSE

Mode	0 Auto	Autos < Adults	Autos >= Adults
SOV	-	-*	-*
HOV2	-*	0.164	0.128
HOV3	-0.027	0.182	0.157
WALK	0.368	0.156	-0.012
BIKE	0.368	0.278	0.332
WLK TRN	-2.117	-1.014	-1.496
PNR TRN	-	-1.048	-0.285
KNR TRN	0.205	-0.963	0.043
SCHBUS	0.920	0.655	0.656

* reference category

TABLE 50. TOUR MODE CHOICE UEC ADJUSTMENTS FOR INDIVIDUAL MAINTENANCE PURPOSE

Mode	0 Auto	Autos < Adults	Autos >= Adults
SOV	-	-*	-*
HOV2	-*	0.141	0.134
HOV3	-0.009	0.139	0.140
WALK	-0.136	-0.118	-0.191
BIKE	-0.627	-0.155	-0.003
WLK TRN	-0.335	-0.306	-0.416
PNR TRN	-	0.536	0.057
KNR TRN	0.101	0.097	0.085
SCHBUS	-	-	-

* reference category

TABLE 51. TOUR MODE CHOICE UEC ADJUSTMENTS FOR INDIVIDUAL DISCRETIONARY PURPOSE

Mode	0 Auto	Autos < Adults	Autos >= Adults
SOV	-	-*	-*
HOV2	-*	0.123	0.122
HOV3	0.055	0.161	0.131
WALK	-0.148	-0.134	-0.210
BIKE	-0.198	0.029	-0.014
WLK TRN	-0.435	-0.497	-0.556
PNR TRN	-	0.373	0.532
KNR TRN	0.245	0.126	0.237
SCHBUS	-	-	-

* reference category

TABLE 52. TOUR MODE CHOICE UEC ADJUSTMENTS FOR JOINT MAINTENANCE PURPOSE

Mode	0 Auto	Autos < Adults	Autos >= Adults
SOV	-	-*	-*
HOV2	-*	-	-
HOV3	-0.103	0.059	0.048
WALK	0.087	-0.153	-0.291
BIKE	-	-	0.063
WLK TRN	-0.710	-0.701	0.030
PNR TRN	-	0.000	0.000
KNR TRN	0.000	-1.535	0.000
SCHBUS	-	-	-

* reference category

TABLE 53. TOUR MODE CHOICE UEC ADJUSTMENTS FOR JOINT DISCRETIONARY PURPOSE

Mode	0 Auto	Autos < Adults	Autos >= Adults
SOV	-	-*	-*
HOV2	-*	-	-
HOV3	0.458	-0.045	0.009
WALK	2.043	-0.249	-0.401
BIKE	-	-	-0.224
WLK TRN	1.084	-0.913	-0.572
PNR TRN	-	0.000	0.000
KNR TRN	2.010	-1.652	0.000
SCHBUS	-	-	-

* reference category

TABLE 54. TOUR MODE CHOICE UEC ADJUSTMENTS FOR AT WORK SUB-TOUR PURPOSE

Mode	0 Auto	Autos < Adults	Autos >= Adults
SOV	-	-*	-*
HOV2	-*	0.095	0.121
HOV3	-	0.131	0.164
WALK	-5.861	-0.035	-0.169
BIKE	-5.767	0.018	-0.170
WLK TRN	-4.761	-0.822	-0.971
PNR TRN	-	-	-
KNR TRN	-	-	-
SCHBUS	-	-	-

* reference category

APPENDIX C.   TRANSPONDER CHOICE MODEL CHANGES

This appendix lists changes made to enable the transponder choice model in the SANDAG ABM. Two types of changes were made:

- Software
- UECs (tour mode and trip mode)

SOFTWARE

To implement the transponder choice model, only minor changes to software were required; these involved exposing the result of the transponder ownership model to the tour and trip mode choice UECs.

UEC

Tour mode choice and trip mode choice UECs were modified. Two new tokens are added in each UEC for every purpose:

- ownsTransponder
- sovtollAvailable

Figure 41 and Figure 42 shows the two tokens for work purpose in tour mode choice UEC

Model	1		WorkTour_ModeChoice		Decision-making-unit	
No	Token		Description	Filter	Formula for variable	
94	ownsTransponder		Result of transponder ownership model (1=owns, 0=not)		@transponderOwnership	

FIGURE 41. A NEW TOKEN 'OWNSTRANSPONDER' – TOUR MODE CHOICE (WORK)

Model	1	WorkTour_ModeChoice		Decision-making-unit		t
No	Token	Description	Filter	Formula for variable		Index
						DRIV
186	sovtollAvailable	Drive alone toll - Unavailable if I-15 and no transponder	sovtollAvailable	if((((DAT_TOLLCOST[outSkim]+DAT_TOLLCOST[inSkim])<10000,)*(ownsTransponder==0)),0,1)		od,do

FIGURE 42. A NEW TOKEN 'SOVTOLLAVAILABLE' – TOUR MODE CHOICE (WORK)

Figure 41 and Figure 42 shows the two tokens for work purpose in trip mode choice UEC.

Model	6		AtWorkTrip_ModeChoice		Decision-making-unit	
No	Token		Description	Filter	Formula for variable	
54	ownsTransponder		Result of transponder ownership model (1=owns, 0=not)		@transponderOwnership	

FIGURE 43. A NEW TOKEN 'OWNSTRANSPONDER' – TRIP MODE CHOICE (WORK)

Model	6	AtWorkTrip_ModeChoice		Decision-making-unit		t
No	Token	Description	Filter	Formula for variable		Index
159	sovtollAvailable	Drive alone toll - Unavailable if I-15 anc	sovtollAvailable	if(((DAT_TOLLCOST[skim]<10000)*(ownsTransponder==0)),0,1)		od

FIGURE 44. A NEW TOKEN 'SOVTOLLAVAILABLE' – TRIP MODE CHOICE (WORK)

APPENDIX D. CHANGES TO THE SANDAG MODEL SYSTEM

This memo describes changes to the SANDAG model system to implement the Strategic Highway Research Project (SHRP) C04 recommendations on model enhancements for pricing and reliability. The memo is organized by three types of changes: Software code, Utility Expression Calculator spreadsheets, and TransCAD GISDK scripts.

SOFTWARE CODE CHANGES

The SANDAG activity-based models are a member of the Coordinated Travel – Regional Activity-Based Modeling Platform (CT-RAMP) family of models. The modeling platform is implemented in the Java programming language. There are two key libraries used in the software; a common modeling framework (package common-base) which contains set of software tools for model application, including a matrix package, a logit model package, a Utility Expression Calculator package which provides the capability to specify logit models in spreadsheets, and other data handling and processing procedures. The SANDAG resident models, as well as other special market models, are implemented in the SANDAG ABM package. Most of the software refactoring was confined to SANDAG-specific code; however, one key change was made to common-base to make a particular method public. This is described in more detail below. TransCAD is used for highway and transit skimming and assignment, as well as aggregate (heavy truck, commercial vehicle, external-internal and external-external) models and trip table processing. While many of the changes described below were made to tour and trip mode choice-related code, tour and stop destination choice and time-of-day choice models are sensitive to these changes due to the use of mode choice logsums in these upper level models.

There are several key changes made to the SANDAG software system:

1) To implement **distributed time coefficients**, codes were written to provide the capability to sample from lognormal distributions and store work and non-work time factors in person objects (or tour objects in the case of the cross-border models). The time factors are exposed in the Decision-Making Unit classes that are used to interface between the model utility equations and the in-memory representation of object (person, tour, and trip) data. This allows time factors to be applied in Utility Equation Calculator (UEC) spreadsheets, which were modified to refer to the time factors and scale the time coefficient for each tour and trip purpose accordingly. Time factors are also written to output person and tour files. These changes affect both resident models (including internal-external mode choice) and Mexican resident\cross-border travel models. Distributed time coefficients are not used in air passenger, visitor, or special event models.

2) To implement changes to the **cost coefficients**, UEC tour and trip mode choice spreadsheets were modified to calculate a cost coefficient based on household income and occupancy. This means that there are three value of time bins for each tour and trip; one for drive-alone tours\trips (which also applies to transit and non-motorized modes), and one for each shared-ride (two and three plus) mode. Cost coefficient changes are limited to tour and trip mode choice UECs for resident models.

3) To implement **value-of-time bins**, GISKDK code was developed to skim and assign three value-of-time bins for the highway mode. This increased the number of highway skims by a factor of 3, from 100 to 300 tables. Relevant UEC spreadsheets were modified to read in the new skims on the data page, and then lines were added to the UEC model page to calculate the value of time bin based on the value-of-time for the decision-maker based on the time and cost coefficient. The UEC refers to thresholds for low and medium value-of-time categories that are set in the properties file to ensure consistency across all of the models. Note that trip tables must also be written out by value-of-time.

In order to do this, the software queries the tour mode UEC after the solve method is called and a mode is chosen. Based on the chosen mode, the code queries the values for the vot, vot2, or vot3 tokens from the UEC variable table, and stores the result in the tour object. This is then written to the output tour and trip lists. The classes that read in the trips and writes out the trip tables by value of time were modified to read the values of time stored in the trip lists and the thresholds for low and medium bins that are stored in the properties file. These changes affect all simulation models including San Diego resident models, Mexican resident travel models, air passenger models, visitor models, and special event models.

SPECIFIC SOFTWARE CHANGES

org.sandag.abm.accessibilities

- AutoAndNonMotorizedSkimsCalculator: Modified getAutoSkims() argument list to add vot (value of time) to argument list. Method sets VOT in the new class AutoSkimsDMU, so that the AutoSkims.xls UEC returns the correct skims for the VOT bin.
- AutoSkimsDMU: A new class that contains getters and setters for vot so that the correct skims can be indexed in the AutoSkims.xls UEC.
- MCLogsumsAppender: Set the direction of the trip in the mode choice DMU object. This is required due to the different cost sensitivity in the inbound versus outbound direction.
- ParkLocationEstimationAppender: Modified class to include a default value-of-time ($15/hr) and use for auto skims.
- SkimsAppender: Modified class to include a default value-of-time ($15/hr) and use for auto skims.
- StopLocationSampleCalculator: Modified class to include a default value-of-time ($15/hr) and use for auto skims.
- TripSkimsAppender: Modified class to include a default value-of-time ($15/hr) and use for auto skims.
- XBorderSkimsAppender: Modified class to include a default value-of-time ($15/hr) and use for auto skims.

org.sandag.abm.airport

- AirportModeChoiceModel: Modified chooseMode() such after the mode is chosen, the UEC is queried to obtain the value of time depending upon the chosen mode. The value of time is then stored in the AirportParty object.
- AirportParty: Added float valueOfTime as a data member, with getter and setter.
- AirportPartyManager: Modified to write valueOfTime in output file.
- AirportTripTables: Modified to write auto trip tables by value of time and set value of time according to the value in the trip file, using the thresholds for low, medium and high VOT classes set in the properties file.

org.sandag.abm.application

- SandagHouseholdDataManager2: Modified such that if inherited data member readTimeFactors is true, sets timeFactorWork and timeFactorNonWork to fields in person file, else sets time factors to 1.0.

- SandagInternalExternalTripChoiceDMU: Modified to store and get household income, for calculation of cost coefficient in internal-external mode choice model.
- SandagTourModeChoiceDMU: Added getWorkTimeFactor(), getNonWorkTimeFactor(), and getJointTourTimeFactor() to methodIndexMap.
- SandagTripModeChoiceDMU: Added getWorkTimeFactor(), getNonWorkTimeFactor(), and getJointTourTimeFactor() to methodIndexMap.
- SandagTripTables: Modified to write auto trip tables by value of time and set value of time according to the value in the trip file, using the thresholds for low, medium and high VOT classes set in the properties file.

org.sandag.abm.crossborder

- CrossBorderTour: Added workTimeFactor, nonWorkTimeFactor, and valueOfTime as data members, with getters and setters.
- CrossBorderTourManager: Modified generateCrossBorderTours() to sample workTimeFactor and nonWorkTimeFactor from lognormal distributions and store in Tour object if distributedTimeCoefficients in properties file is true, else workTimeFactor and nonWorkTimeFactor set to 1.0. Modified writeOutputFile() method to write workTimeFactor, nonWorkTimeFactor, and valueOfTime to output tour and trip files.
- CrossBorderTourModeChoiceModel: Modified to call getValueOfTime(int mode) from CrossBorderTripModeChoiceModel based on chosen tour mode.
- CrossBorderTripModeChoiceDMU: Added workTimeFactor and nonWorkTimeFactor data members and getters and setters. Modified methodIndexMap to return appropriate values.
- CrossBorderTripModeChoiceModel: Added method getValueOfTime() such after the mode is chosen, the UEC is queried to obtain the value of time depending upon the chosen mode. The method is called by CrossBorderTourModeChoiceModel.
- CrossBorderTripTables: Modified to write auto trip tables by value of time and set value of time according to the value in the trip file, using the thresholds for low, medium and high VOT classes set in the properties file.

org.sandag.abm.ctramp

- HouseholdChoiceModels: Added ModelStructure argument to constructor of InternalExternalTripChoice model.
- HouseholdDataManager: Added boolean readTimeFactors member and set based on distributedTimeCoefficients in properties file. Also added names of workTimeFactor and nonWorkTimeFactor fields to read from person file if readTimeFactors is true (this is done in child class SandagHouseholdDataManager2)
- HouseholdDataWriter: Modified writer methods as follows:
  - Person data file modified to include workTimeFactor and nonWorkTimeFactor
  - Individual tour data file modified to include valueOfTime
  - Joint tour data file modified to include valueOfTime
  - Individual trip data file modified to include valueOfTime
  - Joint trip data file modified to include valueOfTime
- IntermediateStopChoiceModels: Modified to call setInbound() method of trip mode choice DMU object, required for applying correct cost coefficient for trips on work tours.
- InternalExternalTripChoiceModel: Added ModelStructure to constructor.

- MandatoryDestChoiceModel: Replaced a call to System.exit() with throw a RuntimeException() for consistent behavior due to crashes.
- Person: Added workTimeFactor and nonWorkTimeFactor members, with getters and setters.
- TimeCoefficientDistributions: A new class that contains lognormal distributions for work and nonwork time factors. The class reads the following new properties in the properties file:
  - timeDistribution.mean.work = 1.0
  - timeDistribution.standardDeviation.work = 0.8
  - timeDistribution.mean.nonWork = 1.0
  - timeDistribution.standardDeviation.nonWork = 1.0
  - timeDistribution.randomSeed = 2301832
- Tour: Added valueOfTime member with getter and setter.
- TourModeChoiceDmu: Added getters and setters for workTimeFactor and nonWorkTimeFactor. Added method to getJointTourTimeFactor() based on age of oldest person in travel party.
- TourModeChoiceModel: Modified chooseMode() such after the mode is chosen, the UEC is queried to obtain the value of time depending upon the chosen mode. The value of time is then stored in the Tour object.
  TripModeChoiceDMU: Added getters and setters for workTimeFactor and nonWorkTimeFactor. Added method to getJointTourTimeFactor() based on age of oldest person in travel party.

org.sandag.abm.internalexternal

- InternalExternalTour: Modified to include nonWorkTimeFactor data member and getter and setter.
- InternalExternalTourManager: Modified generateTours() method such that if distributedTimeCoefficients is true, reads workTimeFactor and nonWorkTimeFactor from input person file; else sets factors to 1.0. Also modified writeOutputFile() method to include value of time in output trip file.
- InternalExternalTrip: Modified to include valueOfTime as data member, with getter and setter.
- InternalExternalTripModeChoiceDMU: Modified to include nonWorkTimeFactor in DMU, with getter and setter and modified methodIndexMap to return nonWorkTimeFactor.
- InternalExternalTripModeChoiceModel: Modified chooseMode() such after the mode is chosen, the UEC is queried to obtain the value of time depending upon the chosen mode. The value of time is then stored in the InternalExternalTrip object.
  InternalExternalTripTables: Modified to write auto trip tables by value of time and set value of time according to the value in the trip file, using the thresholds for low, medium and high VOT classes set in the properties file.

org.sandag.abm.reporting

- DataExporter: Extensive modifications to class to read value of time from input files and use value of time in calls to org.sandag.abm.accessibilities.AutoAndNonMotorizedSkimsCalculator.getAutoSkims(). SkimBuilder: Modified TripAttributes class to include value of time and made ancillary changes to methods.

org.sandag.abm.specialevent

- SpecialEventTour: Modified to include valueOfTime with getter and setter.

- SpecialEventTourManager: Modified to include value of time in output tour and trip files.
- SpecialEventTripModeChoiceModel: Modified chooseMode() such after the mode is chosen, the UEC is queried to obtain the value of time depending upon the chosen mode. The value of time is then stored in the SpecialEventTour object.

org.sandag.abm.visitor

- VisitorTour: Modified to include valueOfTime with getter and setter.
- VisitorTourManager: Modified to include value of time in output tour and trip files.
- VisitorTourModeChoiceModel: Modified chooseMode() such after the mode is chosen, the UEC is queried to obtain the value of time depending upon the chosen mode. The value of time is then stored in the VisitorTour object.
- VisitorTripTables: Modified to write auto trip tables by value of time and set value of time according to the value in the trip file, using the thresholds for low, medium and high VOT classes set in the properties file.

src.test.java\org.sandag.abm.crossborder

- CrossBorderTripModeChoiceDMUTest: test setting and getting work and nonwork time factors.

src.test.java\org.sandag.abm.ctramp

- TimeCoefficientDistributionsTest: A new test class for TimeCoefficientDistributions class.

All revised code has been committed to the develop_enhancetoll branch at github.com\SANDAG\ABM with the Jira ticket ABM-644.

APPENDIX E.   OBSERVED TOLL COSTS ON I15

TABLE 55. NB OBSERVED TOLLS (CENTS) BY TIME PERIOD ON I15 MANAGED LANE FACILITY

Entry	Exit	EA	AM	MD	PM	EV
Ammo Rd NB	Camino Del Norte NB	50	50	87	317	50
Ammo Rd NB	Center City Pkwy NB	80	80	122	465	80
Ammo Rd NB	Del Lago NB Exit	0	75	134	437	75
Ammo Rd NB	Duenda Rd NB	65	65	108	414	65
Ammo Rd NB	Hale Ave NB Exit	95	95	155	543	95
Ammo Rd NB	Miramar Rd NB	50	50	50	70	50
Ammo Rd NB	Rancho Bernardo Transit	55	55	73	359	55
Ammo Rd NB	SR 56-1 NB Exit	50	50	76	230	50
Ammo Rd NB	SR 56-2 NB	50	50	76	278	50
Ammo Rd NB	SR 78	95	95	147	527	95
Camino Del Norte NB	Center City Pkwy NB	50	50	61	165	50
Camino Del Norte NB	Del Lago NB Exit	0	50	57	124	50
Camino Del Norte NB	Duenda Rd NB	50	50	51	79	50
Camino Del Norte NB	Hale Ave NB Exit	50	50	60	208	50
Camino Del Norte NB	Rancho Bernardo Transit	50	50	50	50	50
Camino Del Norte NB	SR 78	50	50	73	234	50
Center City Pkwy NB	Hale Ave NB Exit	50	50	50	63	50
Center City Pkwy NB	SR 78	50	50	51	87	50
Del Lago NB Entry	Center City Pkwy NB	50	50	50	50	50
Del Lago NB Entry	Hale Ave NB Exit	50	50	52	113	50
Del Lago NB Entry	SR 78	50	50	55	109	50
Duenda Rd NB	Center City Pkwy NB	50	50	52	91	50
Duenda Rd NB	Del Lago NB Exit	50	50	50	64	50
Duenda Rd NB	Hale Ave NB Exit	50	50	55	153	50
Duenda Rd NB	SR 78	50	50	62	178	50
I-15 Access	Camino Del Norte NB	60	60	79	380	60
I-15 Access	Center City Pkwy NB	90	90	128	547	90
I-15 Access	Del Lago NB Exit	80	80	122	511	80
I-15 Access	Duenda Rd NB	75	75	113	481	75
I-15 Access	Hale Ave NB Exit	100	100	143	601	100
I-15 Access	Miramar Rd NB	50	50	55	137	50
I-15 Access	Rancho Bernardo Transit	65	65	77	428	65
I-15 Access	SR 56-1 NB Exit	50	50	69	267	50
I-15 Access	SR 56-2 NB	50	50	76	347	50
I-15 Access	SR 78	100	100	157	576	100
Mira Mesa Bl NB	Camino Del Norte NB	0	50	76	244	50
Mira Mesa Bl NB	Center City Pkwy NB	65	66	109	420	65
Mira Mesa Bl NB	Del Lago NB Exit	0	55	94	341	55

Entry	Exit	EA	AM	MD	PM	EV
Mira Mesa Bl NB	Duenda Rd NB	0	52	102	336	50
Mira Mesa Bl NB	Hale Ave NB Exit	75	81	166	519	75
Mira Mesa Bl NB	Rancho Bernardo Transit	50	50	59	242	50
Mira Mesa Bl NB	SR 56-1 NB Exit	0	50	52	108	50
Mira Mesa Bl NB	SR 56-2 NB	50	50	55	141	50
Mira Mesa Bl NB	SR 78	75	75	128	463	75
Miramar Rd NB	Camino Del Norte NB	50	50	82	298	50
Miramar Rd NB	Center City Pkwy NB	70	70	121	495	70
Miramar Rd NB	Del Lago NB Exit	0	65	122	444	65
Miramar Rd NB	Duenda Rd NB	0	55	109	390	55
Miramar Rd NB	Hale Ave NB Exit	0	85	148	600	85
Miramar Rd NB	Rancho Bernardo Transit	0	50	71	314	50
Miramar Rd NB	SR 56-1 NB Exit	0	50	72	188	50
Miramar Rd NB	SR 56-2 NB	50	50	67	221	50
Miramar Rd NB	SR 78	85	85	153	576	85
Rancho Bernardo Transit	Center City Pkwy NB	50	50	59	148	50
Rancho Bernardo Transit	Del Lago NB Exit	0	50	53	115	50
Rancho Bernardo Transit	Duenda Rd NB	0	50	50	62	50
Rancho Bernardo Transit	Hale Ave NB Exit	0	50	73	237	50
Rancho Bernardo Transit	SR 78	0	50	71	229	50
Sabre Springs Transit	Camino Del Norte NB	0	50	53	79	50
Sabre Springs Transit	Center City Pkwy NB	50	50	62	240	50
Sabre Springs Transit	Del Lago NB Exit	50	50	78	227	50
Sabre Springs Transit	Duenda Rd NB	50	50	71	163	50
Sabre Springs Transit	Hale Ave NB Exit	0	60	74	325	60
Sabre Springs Transit	Rancho Bernardo Transit	0	50	51	102	50
Sabre Springs Transit	SR 56-2 NB	50	50	50	50	50
Sabre Springs Transit	SR 78	60	60	139	308	60
SR 163 Access	Camino Del Norte NB	55	55	81	350	55
SR 163 Access	Center City Pkwy NB	0	85	129	528	85
SR 163 Access	Del Lago NB Exit	0	80	142	496	80
SR 163 Access	Duenda Rd NB	70	70	113	465	70
SR 163 Access	Hale Ave NB Exit	0	100	153	643	100
SR 163 Access	Miramar Rd NB	50	50	53	104	50
SR 163 Access	Rancho Bernardo Transit	60	60	88	379	60
SR 163 Access	SR 56-1 NB Exit	50	50	71	271	50
SR 163 Access	SR 56-2 NB	50	50	76	300	50
SR 163 Access	SR 78	100	100	165	578	100
SR 56-2 NB	Camino Del Norte NB	50	50	50	60	50
SR 56-2 NB	Center City Pkwy NB	50	50	68	202	50
SR 56-2 NB	Del Lago NB Exit	50	50	70	168	50
SR 56-2 NB	Duenda Rd NB	50	50	57	128	50

Entry	Exit	EA	AM	MD	PM	EV
SR 56-2 NB	Hale Ave NB Exit	0	55	85	288	55
SR 56-2 NB	Rancho Bernardo Transit	50	50	51	79	50
SR 56-2 NB	SR 78	55	55	89	276	55

TABLE 56. SB OBSERVED TOLLS (CENTS) BY TIME PERIOD ON I15 MANAGED LANE FACILITY

Entry	Exit	EA	AM	MD	PM	EV
9th Ave SB	Camino Del Norte SB	50	229	50	50	50
9th Ave SB	Del Lago SB Exit	50	61	50	50	50
9th Ave SB	Duenda Rd SB	50	158	50	50	50
9th Ave SB	Mercy Rd-1 SB	63	368	60	60	60
9th Ave SB	Miramar Rd SB	77	447	76	75	75
9th Ave SB	Poway Rd SB	57	331	55	55	55
9th Ave SB	Rancho Bernardo Transit	51	176	51	50	50
9th Ave SB	Sabre Springs Transit	50	268	50	50	50
9th Ave SB	SR 163 Access	93	469	91	90	90
9th Ave SB	SR 56 SB	51	278	51	50	50
Camino Del Norte SB	Mercy Rd-1 SB	50	144	50	50	50
Camino Del Norte SB	Miramar Rd SB	50	243	52	51	50
Camino Del Norte SB	Poway Rd SB	50	138	50	50	50
Camino Del Norte SB	Sabre Springs Transit	50	76	50	50	50
Camino Del Norte SB	SR 163 Access	51	326	54	51	50
Camino Del Norte SB	SR 56 SB	50	70	50	50	50
Del Lago SB Entry	Camino Del Norte SB	53	195	51	50	50
Del Lago SB Entry	Duenda Rd SB	50	106	50	50	50
Del Lago SB Entry	Mercy Rd-1 SB	58	361	51	50	50
Del Lago SB Entry	Miramar Rd SB	89	451	70	65	65
Del Lago SB Entry	Poway Rd SB	53	340	52	50	50
Del Lago SB Entry	Rancho Bernardo Transit	50	142	50	50	50
Del Lago SB Entry	Sabre Springs Transit	50	291	53	50	50
Del Lago SB Entry	SR 163 Access	89	523	84	80	80
Del Lago SB Entry	SR 56 SB	50	285	50	50	0
Duenda Rd SB	Camino Del Norte SB	50	102	50	50	50
Duenda Rd SB	Mercy Rd-1 SB	51	251	52	50	50
Duenda Rd SB	Miramar Rd SB	52	343	52	51	50
Duenda Rd SB	Poway Rd SB	51	220	51	50	50
Duenda Rd SB	Rancho Bernardo Transit	50	50	50	50	50
Duenda Rd SB	Sabre Springs Transit	50	156	50	50	50
Duenda Rd SB	SR 163 Access	72	411	69	67	65
Duenda Rd SB	SR 56 SB	50	164	50	50	50
Hale Ave SB Entry	9th Ave SB	50	67	50	50	50

Entry	Exit	EA	AM	MD	PM	EV
Hale Ave SB Entry	Camino Del Norte SB	67	311	50	50	50
Hale Ave SB Entry	Del Lago SB Exit	0	111	50	50	50
Hale Ave SB Entry	Duenda Rd SB	50	211	50	50	50
Hale Ave SB Entry	Mercy Rd-1 SB	79	477	70	70	70
Hale Ave SB Entry	Miramar Rd SB	85	530	86	85	85
Hale Ave SB Entry	Poway Rd SB	65	413	66	65	0
Hale Ave SB Entry	Rancho Bernardo Transit	50	279	50	50	0
Hale Ave SB Entry	Sabre Springs Transit	60	361	60	60	60
Hale Ave SB Entry	SR 163 Access	102	548	100	100	100
Hale Ave SB Entry	SR 56 SB	60	430	60	60	0
Mercy Rd-1 SB	Miramar Rd SB	50	108	51	50	0
Mercy Rd-1 SB	SR 163 Access	50	170	52	51	50
Mercy Rd-2 SB	Miramar Rd SB	50	64	50	50	50
Mercy Rd-2 SB	SR 163 Access	50	148	51	50	50
Miramar Rd SB	SR 163 Access	50	74	50	50	50
Poway Rd SB	Mercy Rd-1 SB	50	50	50	50	50
Poway Rd SB	Miramar Rd SB	50	137	51	50	50
Poway Rd SB	SR 163 Access	50	199	55	52	50
Rancho Bernardo Transit	Camino Del Norte SB	0	73	50	50	50
Rancho Bernardo Transit	Mercy Rd-1 SB	50	228	50	50	50
Rancho Bernardo Transit	Miramar Rd SB	0	330	51	50	50
Rancho Bernardo Transit	Poway Rd SB	53	233	51	50	50
Rancho Bernardo Transit	Sabre Springs Transit	50	124	50	50	50
Rancho Bernardo Transit	SR 163 Access	66	420	64	61	60
Rancho Bernardo Transit	SR 56 SB	50	158	50	50	50
Sabre Springs Transit	Mercy Rd-1 SB	50	85	50	50	50
Sabre Springs Transit	Miramar Rd SB	50	202	56	50	50
Sabre Springs Transit	Poway Rd SB	50	83	50	50	50
Sabre Springs Transit	SR 163 Access	50	295	57	51	50
SR 56 SB	Mercy Rd-1 SB	50	79	50	50	50
SR 56 SB	Miramar Rd SB	50	178	52	50	50
SR 56 SB	Poway Rd SB	50	51	50	50	50
SR 56 SB	SR 163 Access	53	273	56	52	50
SR 78	9th Ave SB	50	66	50	50	50
SR 78	Camino Del Norte SB	53	283	50	50	50
SR 78	Del Lago SB Exit	50	106	50	50	50
SR 78	Duenda Rd SB	50	215	50	50	50
SR 78	Mercy Rd-1 SB	73	430	70	70	70
SR 78	Miramar Rd SB	90	498	86	85	85
SR 78	Poway Rd SB	68	391	66	65	65
SR 78	Rancho Bernardo Transit	53	240	50	50	50
SR 78	Sabre Springs Transit	64	352	61	60	60

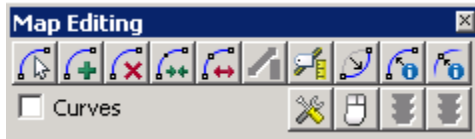| Entry	Exit	EA	AM	MD	PM	EV
SR 78	SR 163 Access	104	506	101	100	100
SR 78	SR 56 SB	61	346	61	60	60

APPENDIX F. EDITING A HIGHWAY DATABASE IN TRANSCAD

First, enable the editing tool as below:

Tools → Map Editing → Toolbox
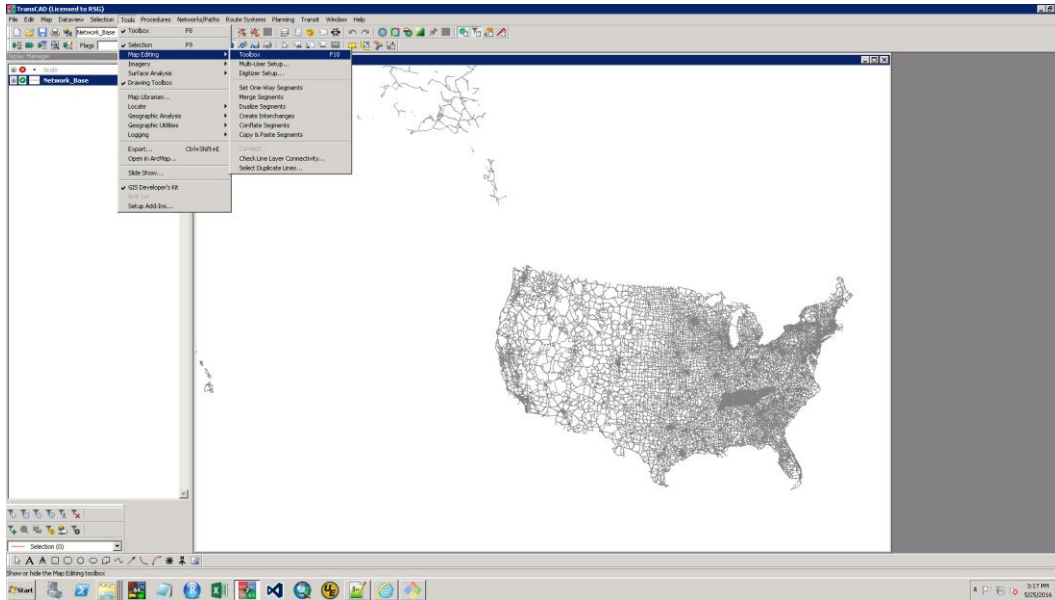
This brings up a toolbox:

Function of each of the options can be viewed by just hovering over mouse pointer. For this exercise you will need three editing options:

- Add line
- Delete line
- Edit Line Attributes

In addition, you will also need the info option top view and edit link attributes

So, the idea here is to create new entry/exit links that would replace existing links. As new links would need attributes, we would copy those from old links. To do so, we need to view old link attributes and copy for later use.

To copy an existing link attributes, click on info and click on the existing link you want to replace. Now, select all attributes after QID and hit CTRL+C (copy) on your keyboard. This will copy the attributes of this link.

Now go to the location you want to add a new link and Click on .
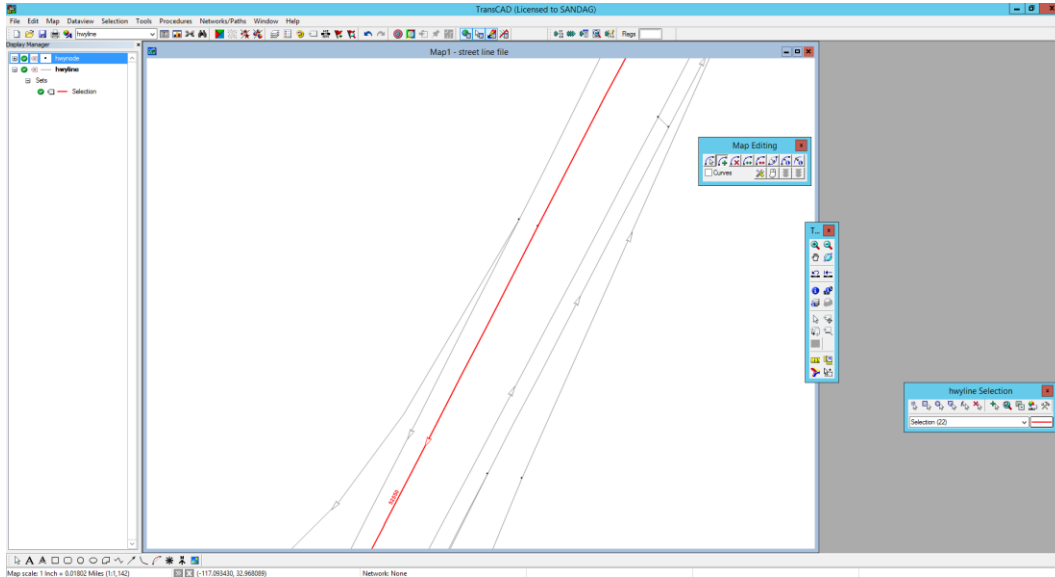
Now, click on "from node" and "to node" and hit ENTER on your keyboard. This will add a new line.
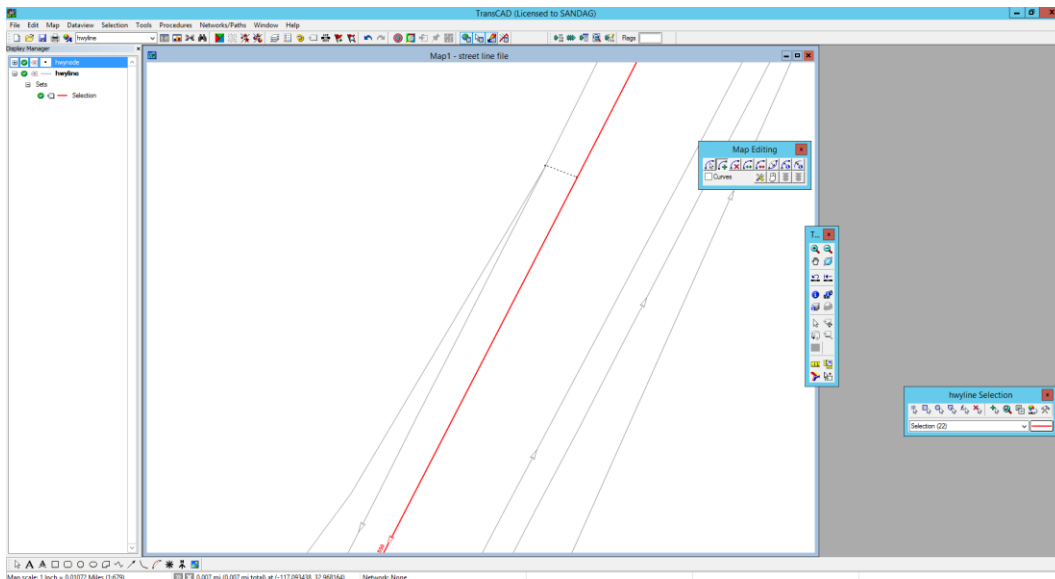

To save the edits, click on SAVE in the Map Editing toolbox.

If there is no existing node at the location, clicking on "to/from link" would split the link and add a new node. Note that (by default) only one of the split links would have old link attributes, the other link would have no attributes and you would need to populate those attributes by copying from the first link. However, you can change the way link attributes are updated after split. To do so, go to settings in the Map Editing toolbox and click on "Update" under "Options"
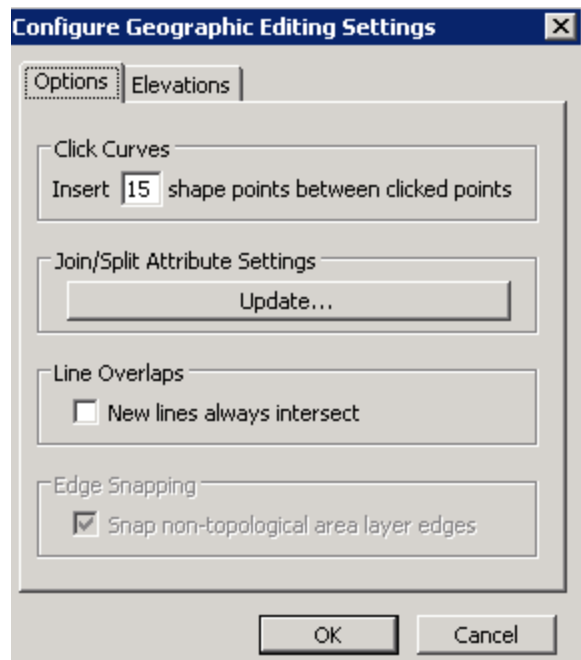
This will bring the following window:
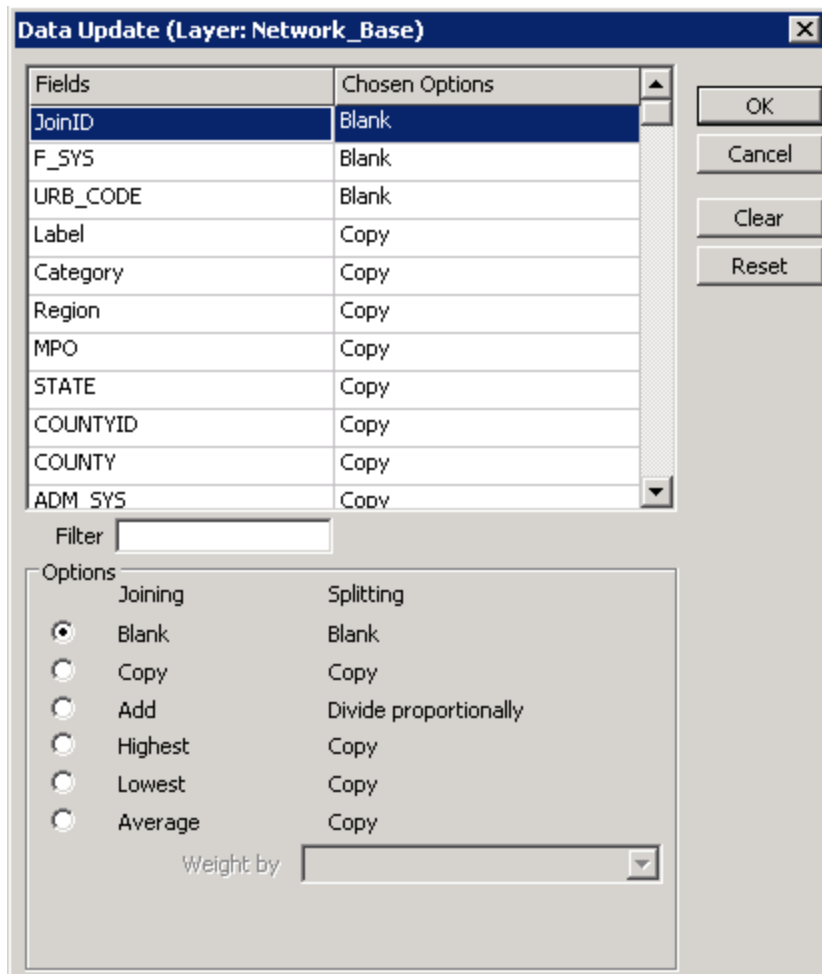
For each link attributes, an option (blank, copy, add, highest, lowest, average) can be chosen.

Now, you would need to update the link attributes. To do so, click on "Edit Line Attributes" and paste the values (copied from old link) in field "QID".

Now, we also need to update the link direction as, by default, TransCAD adds a two way link. Go to line info using the info tool and update the field "Dir".

Note that presently, SANDAG has only two "Dir" values (0 – two way or 1-one way AB direction), so make sure that the from and to nodes are chosen accordingly when adding the link. This is important as GISDK scripts in some places assumes that "Dir" field is either 0 or 1. A value of -1 (BA direction) is not expected by GISDK.

At the end, delete the old link by using Delete line tool and selecting the old link. To finish, save the edits using SAVE.

Note that the SANDAG line layer has a few fields, that may need to be updated manually:

- IWAY – used to populate Dir field.
- AN – from node
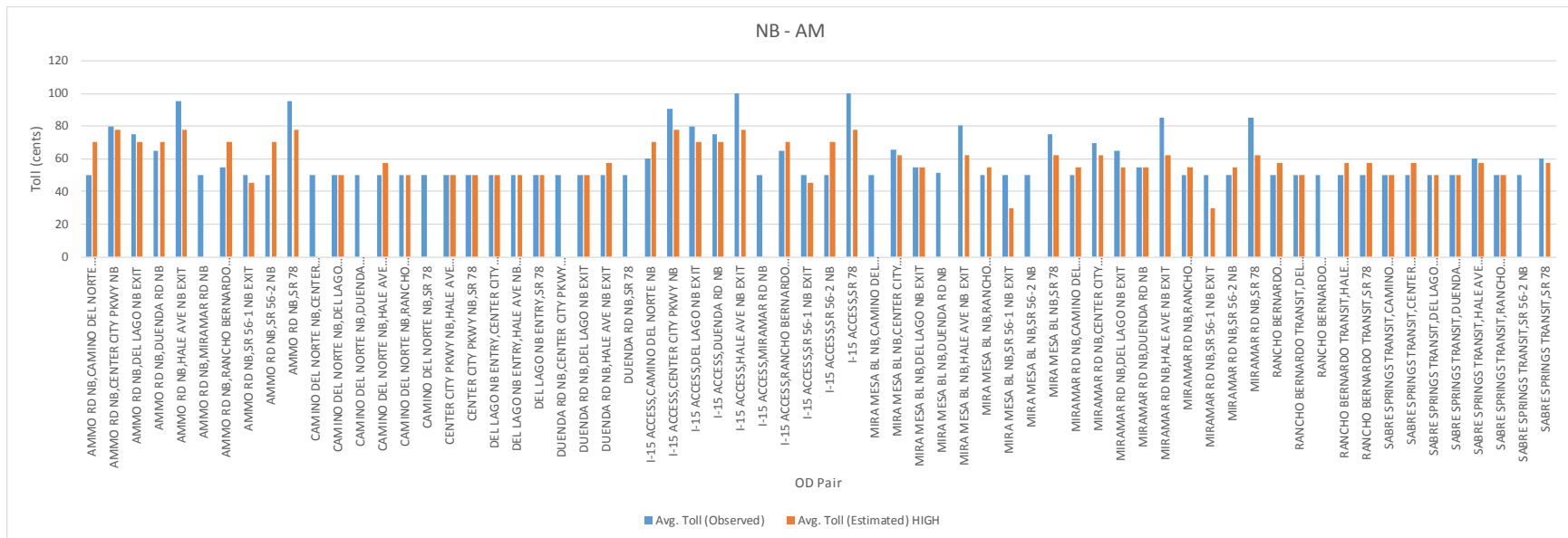- BN – to node

APPENDIX G. I15 ESTIMATED TOLLS

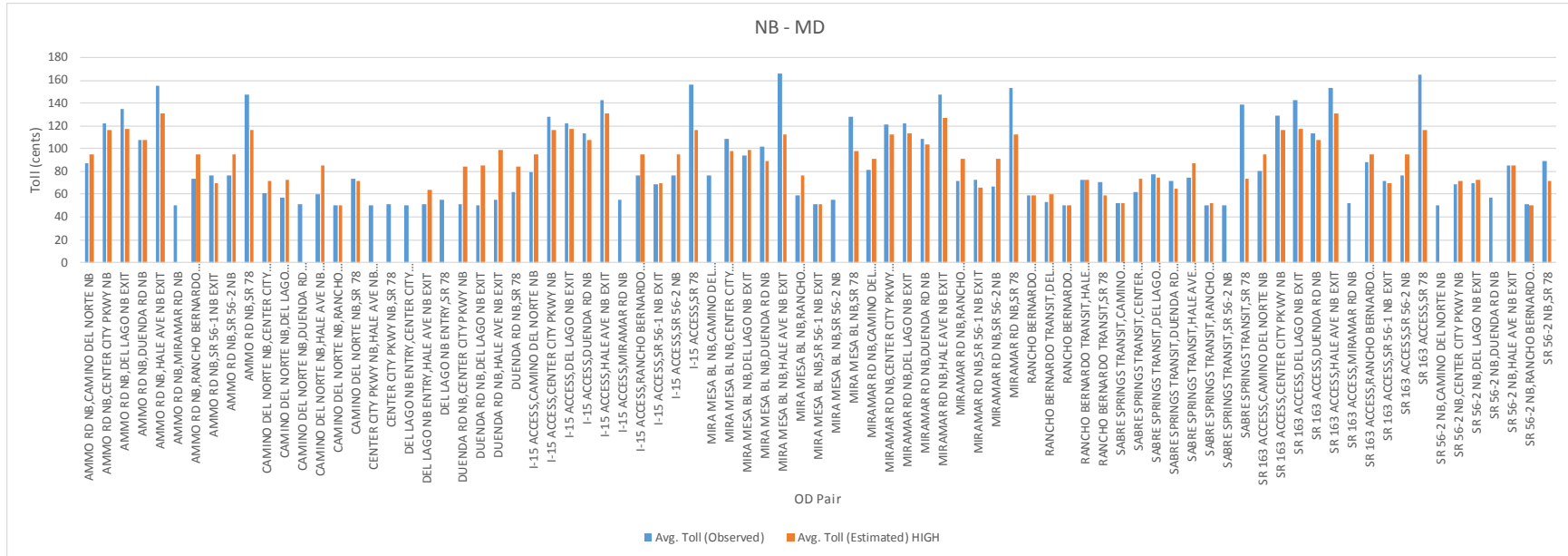**FIGURE 45. NB ESTIMATED TOLLS ON I15 DURING AM PERIOD**

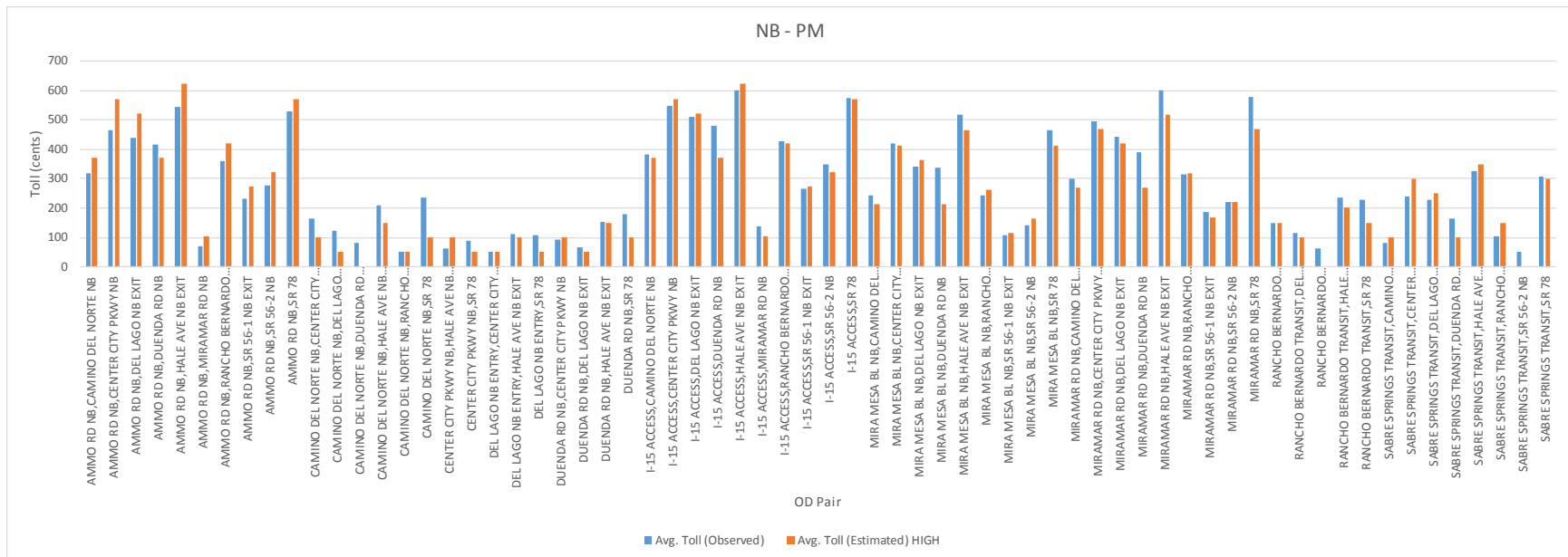**FIGURE 46. NB ESTIMATED TOLLS ON I15 DURING MD PERIOD**
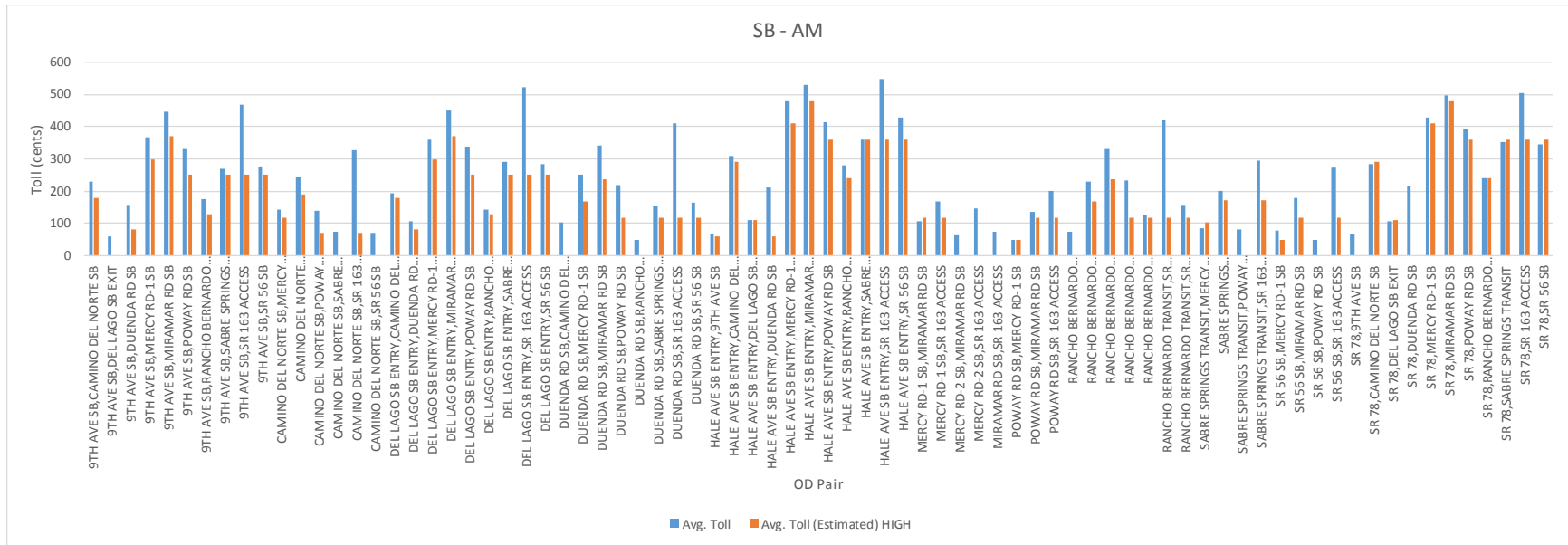
FIGURE 47. NB ESTIMATED TOLLS ON I15 DURING PM PERIOD

FIGURE 48. SB ESTIMATED TOLLS ON I15 DURING AM PERIOD

FIGURE 49. SB ESTIMATED TOLLS ON I15 DURING MD PERIOD

SB - PM

FIGURE 50. SB ESTIMATED TOLLS ON I15 DURING PM PERIOD