



**SACRAMENTO AREA COUNCIL OF  
GOVERNMENTS**

# **TRAVEL DEMAND MODEL TOLL ENHANCEMENTS**

**Technical Memorandum | September 20, 2018**



**PREPARED FOR:**  
SACRAMENTO AREA COUNCIL OF GOVERNMENTS

**SUBMITTED BY:**  
RSG

55 Railroad Row  
White River Junction, VT 05001  
802.295.4999  
[www.rsginc.com](http://www.rsginc.com)





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## 1.0 INTRODUCTION

This technical memorandum describes enhancements made to the Sacramento Area Council of Governments (SACOG) travel demand model (SacSim), related to modeling tolls. These enhancements are based largely on the recommendations of the Strategic Highway Research Program C04 project on pricing and reliability. 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.

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

Where:

- $\Delta$  = 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

**Commented [GU1]:** Further documentation detailing out sources. What comes from SHRP CO4 recommendations, surveys, RSG or other pricing enhancement projects/observations.

**Commented [JF2R1]:** Added detail about SHRP C04

The formula has several interesting features. First, the report recommends a random coefficient on travel time to reflect unobserved user heterogeneity. 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.

Second, the recommended highway utility function suggests that travel time sensitivity should be a function of distance. The recommended parameters result 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, and then decreasing until travelers are approximately 0.7 times as sensitive to travel time at 80 miles. Since other studies (4) demonstrate increasing values of time with respect to trip distance, we did not implement the SHRP C04 distance-based travel time sensitivities.

Third, the C04 report recommends scaling the travel cost coefficient by a function of household income and auto occupancy. Sensitivity to cost by income and occupancy is common practice in travel models and well-supported by theory.

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. In lieu of a DTA model, which is not available for this project, the C04 report suggest using congestion as a proxy for reliability with time factors that range from 1.05 to 1.80 based on traffic conditions. This approach may be reasonable given that unreliability of travel time tends to increase with respect to traffic congestion.

The SHRP C04 enhancements implemented in the SACOG travel demand model system include changes to the distribution of value-of-time (VOT) in the DaySim model and the implementation of value-of-time bins in auto trip assignment and level-of-service matrix calculations implemented in Cube. These enhancements were previously introduced in a previous version of SacSim, and fully tested and revised in the current version. In this version of the models, an innovative toll adjustment algorithm was also implemented, to calculate tolls that are consistent with the demand assigned to the auto network.

This memorandum proceeds in the following sections: 1) analysis of the value-of-time distribution in the initial model and revisions to the value-of-time distribution; 2) modifications made to the auto network to enable the revised auto skimming and assignment steps. 3) the toll optimization procedure is described. Finally, the memorandum offers some concluding remarks.



## 2.0 VOT ANALYSIS AND UPDATE

### Value of Time Distributions

SacSim uses distributed travel time sensitivities that are drawn from a lognormal distribution whose shape is controlled by the user. In the initial model, the values-of-time (VOT) for mandatory and non-mandatory SacSim trips were drawn from log normal distributions with standard deviations equal to 0.24 and 0.15 respectively. Comparison of the resulting distributions of value-of-time with that of other regions collected by RSG indicated the need for increasing the standard deviation for SacSim trips. Several trials were run with different values of standard deviation and compared against the other regions' distributions. A standard deviation of 0.85 was selected for both mandatory and non-mandatory trips in the current version. Figure 1 shows the initial and final value-of-time distributions for trips by tour type (mandatory versus non-mandatory). As shown in the plot, the new distributions use a higher standard deviation and therefore shift trips to the left (more trips with lower value-of-time than the initial distributions). These plots more closely match the results of several Stated Preference surveys conducted by RSG over the past several years<sup>1</sup>.

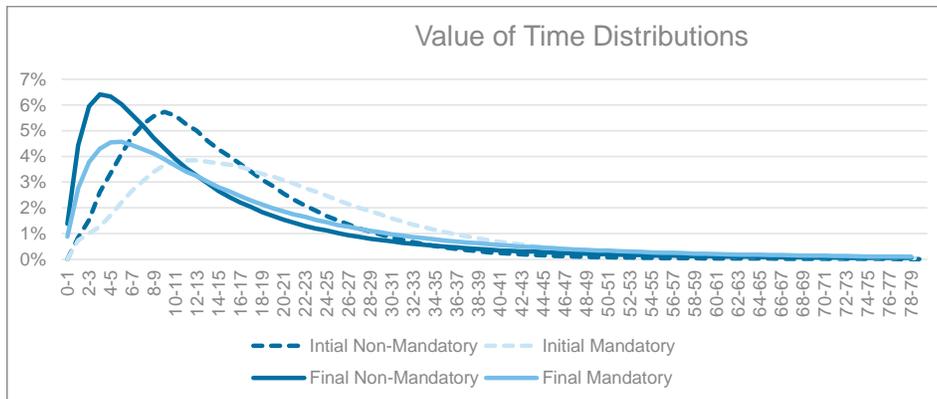


FIGURE 1: INITIAL VERSUS FINAL VALUE-OF-TIME DISTRIBUTIONS

<sup>1</sup> Stated preference survey value-of-time distributions are omitted due to confidentiality.

## Auto Value-of-Time Bins

The initial model setup used one value-of-time to determine path choice for all trips in the model. In the new model setup, three VOT bins were created for highway skimming and assignment. The bins were created using 33<sup>rd</sup>, 66<sup>th</sup> and 90<sup>th</sup> percentile values of the values-of-time for all trips. The corresponding dollar amount of the percentiles were \$7.25, \$16.85 and \$38.80 respectively. These bins were used to group all trips into three VOT classes; low (1), medium (2) and high (3). The resulting cube script skims time, distance, and toll cost for three occupancy groups (drive alone, shared ride-2 and shared ride 3+) and 9 time periods for each of the three VOT classes. The total number of skim matrices thus produced is 243. A generalized cost function was used to find the shortest path that considers both time and cost, as follows:

$$\text{cost} = \text{time} + (\text{AOC} + \text{toll}) * \text{VOT}_i$$

where:

cost is the generalized cost on the link in minutes

time is the congested time on the link returned by the volume-delay function

AOC is the auto operating cost on the link, in dollars

VOT<sub>i</sub> is the value-of-time on the link, in minutes per dollar.

The VOTs used for the three classes are:

- Low VOT bin:  $60/7.25 = 8.28 \text{ min}/\$$
- Medium VOT bin:  $60/16.85 = 3.56 \text{ min}/\$$
- High VOT bin:  $60/38.80 = 1.55 \text{ min}/\$$



### 3.0 NETWORK MODIFICATIONS

The initial setup used network fields such as *no\_da*, *no\_s2* and *no\_s3* to represent occupancy restrictions in the links. A new network field named *USECLASS* was created to replace the previously mentioned fields. *USECLASS* can take three values:

- *USECLASS*=0 corresponds to a general-purpose link
- *USECLASS*=2 corresponds to a shared ride 2+ facility
- *USECLASS* 3 corresponds to a shared ride 3+ link.

Additional network fields were introduced to enable the toll optimization algorithm. These fields are used to identify toll segments (segments to be priced on either toll facilities or HOT lanes) and general purpose links corresponding to each toll segment. The corresponding general purpose facility links are used to calculate a travel time savings for each toll segment, which is used to set the toll price in the optimization algorithm.

TOLLID is coded on toll links to identify each toll segment. Each link on the segment should have the same TOLLID. Currently the maximum toll segment ID is 100, but this can easily be increased in the Cube script.

GPID is used to represent the general-purpose links parallel to the toll links. It must correspond exactly to TOLLID for any TOLLID segment that is to be optimized in the toll optimization algorithm. The total length of all links for each segment should be generally equal between the toll links (identified with TOLLID>0) and general purpose links (identified with GPID>0).

A toll cost file (*tolls.csv*) contains the initial values to be used by the toll optimization algorithm. The toll cost file contains the initial toll, minimum toll and maximum toll for each occupancy class, for each toll segment. The file has 36 rows and 17 columns. The 36 rows contain toll values for the 4 segments for 9 time periods. The first 4 rows of the file are shared below.

Fac. Index	Seg.	Per.	Fac. Type	Adjust	Toll DA	Toll S2	Toll S3	Toll CV	Min DA	Min S2	Min S3	Min CV	Max DA	Max S2	Max S3	Max CV
101	1	1	2	1	1	0	0	2	0.1	0	0	0.2	30	0	0	30
201	2	1	2	1	1	0	0	2	0.1	0	0	0.2	30	0	0	30
301	3	1	2	1	1	0	0	2	0.1	0	0	0.2	30	0	0	30
401	4	1	2	1	1	0	0	2	0.1	0	0	0.2	30	0	0	30

#### Description of the Fields

- Facility Index: A combined index to represent segment and period (segment\*100+period)
- Segment: The toll segment

- Period: Period of the day
- Facility Type: 1=Toll Road, 2=HOT lane
- Adjust: A binary (0,1) variable indicating whether to adjust this segment's toll cost in the toll optimization algorithm
- Toll\_class: Initial toll for different occupancy classes (DA, S2, S3, CV)
- Min\_class: Minimum toll for different occupancy classes (DA, S2, S3, CV)
- Max\_class: Maximum toll for different occupancy classes (DA, S2, S3, CV)

In order to code the file for a toll facility in which all vehicles are tolled, regardless of class, set the initial, minimum, and maximum toll for each occupancy group to be the same. To represent an S2+ HOT lane facility, set the initial, minimum, and maximum toll for DA (make sure that the min\_DA toll is greater than zero), but set the initial, minimum, and maximum toll for S2 and S3 classes to zero. For a S3+ facility, set the initial, min, and max values for DA and S2 to values greater than zero but set the S3 initial, min, and max values to zero.

The per-mile network toll fields (TOLLDA, TOLLS2, TOLLS3, TOLLCV) are set by Cube according to the values in this file; Cube reads the file and sets the fields based on the length of each link compared to the total segment length. These values are overwritten after every toll optimization loop, as the toll values reach optima, as described below. The final output networks from this step are named as `vo.@per@.net`. There are more output networks named `vo.@period@_@iter.i@.net` that are written out in the highway skimming step for each global iteration and `vo.@per@.out.net` which are written out during apportioning new tolls during each iteration. Each `vo.@per@.out.net` is then copied as `vo.@per@.net`, this is done since Cube does not allow reading in and writing out networks with the same names.

Commented [JF3]: What are the field names

Commented [GU4]: Provide documentation on network final results and fields. e.g. which networks are the final output? What are the differences between `vo.period.net`, `vo.period.out.net`, `vo.period_7.net`?



## 4.0 TOLL OPTIMIZATION PROCEDURE

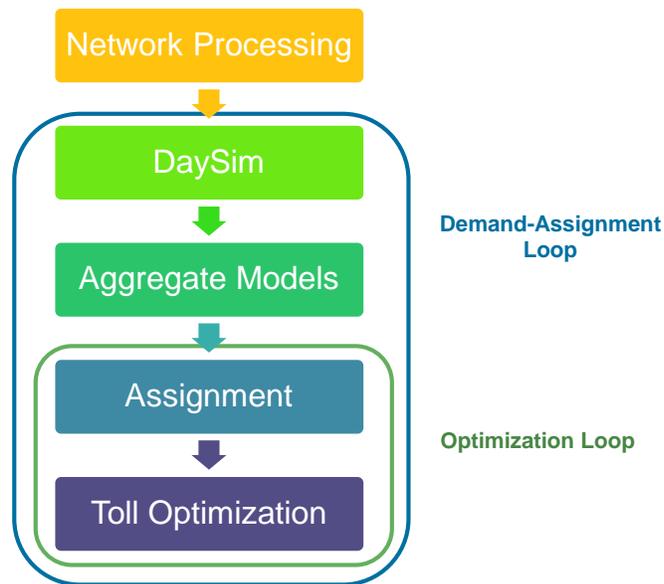
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The purpose of the toll optimization algorithm is to find an optimal toll so that the toll links have an optimal volume; the maximum volume on the link that maintains a minimum level of service as a priced facility. A good starting point for the toll is the value of the time savings offered by the facility. This can be calculated using an average value-of-time for the region, across all purposes and value-of-time bins, by comparing the time on the facility to the time on parallel general purpose lanes. However, it is possible that this toll value would result in an unacceptably low level of service on the facility. If this occurs, the toll needs to be increased to price out users whose value-of-time is lower than the tolled value of the time savings.

The toll optimization algorithm works as a loop within which highway assignments take place. After every assignment, the time savings in the toll segment is measured and the toll is calculated by multiplying the time savings by the average value-of-time. This toll is used in the impedance function for the assignment and only VOT classes with higher values of time than the time-savings-toll take the toll path. If the  $v/c$  ratio in any link of the toll segment exceeds the cutoff value (currently set to 0.8, LOS D or better), the current toll is incremented by a multiplicative factor. In the next loop, the increased toll reduces the attractiveness of the toll segment and  $v/c$  is expected to decrease. The loop continues until the maximum toll change for any segment (new toll – previous toll) is less than 50 cents or after 5 loops in the current setting. Once the toll optimization loop is complete, the program then runs the iteration loop (demand-assignment loop). The following diagram describes the working mechanism of the toll optimization algorithm.

The working mechanism of the algorithm can be summarized by the following steps.

1. Start the toll optimization loop.
2. Read initial tolls for each segment from the tolls.csv file.
3. Calculate the travel time on the toll segments and the corresponding gp segments.
4. Calculate the time savings in the toll segment ( $\text{tollseg\_time} - \text{gpseg\_time}$ )
5. Multiply the time savings by the average VOT to get the current toll.
6. If the v/c ratio in any link of the toll segment is greater than 0.8, multiply the current toll by 2 (or any other factor).
7. Calculate new toll by taking an average of the previous toll and the current toll.
8. Apportion the segment toll to each link in the segment.
9. If the maximum change in tolls from the previous step is less than 50 cents, break the loop.



10. Repeat steps 1 through 6.

During each optimization loop, results are written out to files named **nextToll.per.loop#.csv** which contain the travel times in toll and gp segments, new values of tolls, and the volume in the most congested link in the segment. The following tables show the information contained in each output file during the optimization procedure. Values in these tables correspond to period h01 and loop 1.

**TABLE 1 NEXTTOLL.H09.LOOP1.CSV**

segment	toll_time	gp_time	time_saved	voToll	maxvoc	tollDA	tollS2	tollS3	tollCV	maxTollChange
1	3.21	3.33	0.12	0.04	0.79	0.11	0	0	0.16	0.01
2	3.33	3.56	0.24	0.07	0.69	0.11	0	0	0.16	0.01
3	4.78	6.07	1.29	0.38	0.79	0.61	0	0	0.92	0.23
4	4.09	4.24	0.15	0.04	0.76	0.11	0	0	0.16	0.23

segment	vol_da_lo	vol_cv2_lo	vol_cv3_lo	vol_s2_lo	vol_s3_lo	vol_da_mid	vol_cv2_mid	vol_cv3_mid	vol_s2_mid	vol_s3_mid
1	0	0	0	219	75	33	5	1	345	149
2	0	0	0	145	49	0	0	0	207	89
3	0	0	0	257	89	24	4	1	348	152
4	0	0	0	236	78	0	0	0	272	122

segment	vol_da_hi	vol_cv2_hi	vol_cv3_hi	vol_s2_hi	vol_s3_hi	total_volume
1	231	90	3	220	129	1552
2	281	277	17	106	65	1392
3	211	91	2	207	126	1563
4	210	232	1	141	90	1502

Since DA, CV2 and CV3 are tolled, vehicles of these categories in the low VOT class are priced out of the toll segments, hence it is observed that their volumes in the segment is 0. Vehicles of S2 and S3 categories are observed in the toll segment, as they are not tolled. For medium VOT class, some volume is observed in the toll segment and for the high VOT class, significant volume is observed in each segment due to their higher value of time and willingness to pay the toll.

## 5.0 TOLL OPTIMIZATION TEST RESULTS

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Tables 2 and 3 summarize the toll optimization results using period h09 (9 AM – 10 AM) as an example. Let's look at how the toll is adjusted for segment 3. In the first loop, it is observed that the maxvoc<sup>2</sup> is less than the threshold (0.8) in all segments. In the second loop, maxvoc for segment 3 (0.85) increased above the threshold, so the algorithm incremented the initial toll (previous toll) by a factor (2.0) and took an average of the incremented toll and the previous toll for setting the new toll value.

for loop 2,

initial toll (previous toll from loop 1) = 0.61

vot toll = 0.28

max voc = 0.85

since (initial toll > VOT toll) and (max voc > threshold)

nextToll = initial toll \* 2.0 = 0.61 \* 2.0 = 1.22

avgToll = (nextToll + initial toll)/2 = (1.22 + 0.61)/2 = 0.92

The purpose of incrementing the toll was to bring the v/c ratio below the threshold. In the next loop (loop 3), it is observed that v/c ratio is down to 0.78 for segment 3. A new condition has been added (not reflected in these results) to the script that breaks the optimization loop is the maximum toll change<sup>3</sup> is less than 50 cents. This new condition would break the loop as maxtollchange values are less than 0.50 to reduce run time of the model.

The optimization loops continue until this condition is met or the user defined maximum number of loops is reached.

---

<sup>2</sup> MaxVOC is the maximum volume-to-capacity ratio for any toll link that is part of a toll segment in the given time period.

<sup>3</sup> Maximum toll change (maxtollchange) is calculated as the maximum absolute change in toll for any segment in the given time period.

Commented [GU5]: How are these calculated? maxvoc, maxtollchange

**TABLE 2 TOLL OPTIMIZATION LOOPS FOR PERIOD 3 (H09) (FILE: NEXTTOLL.H09.LOOP1-5.CSV)**

Commented [GU6]: Are these tables provided as a rollup output from the toll optimization loops? filename?

Commented [JF7R6]: Filename is given in the table name

toll loop	segment	tollsegtime	gpsegtime	timesavings	vottoll	maxvoc	da	s2	s3	cv	maxtollchange
Loop 1	1	3.21	3.33	0.12	0.04	0.79	0.11	0	0	0.16	0.01
	2	3.33	3.56	0.24	0.07	0.69	0.11	0	0	0.16	0.01
	3	4.78	6.07	1.29	0.38	0.79	0.61	0	0	0.92	0.23
	4	4.09	4.24	0.15	0.04	0.76	0.11	0	0	0.16	0.23
Loop 2	1	3.2	3.35	0.15	0.04	0.79	0.11	0	0	0.16	0.01
	2	3.33	3.56	0.24	0.07	0.7	0.11	0	0	0.16	0.01
	3	4.9	5.85	0.95	0.28	0.85	0.92	0	0	1.37	0.31
	4	4.07	4.25	0.18	0.05	0.74	0.11	0	0	0.16	0.31
Loop 3	1	3.18	3.36	0.17	0.05	0.77	0.11	0	0	0.16	0.01
	2	3.33	3.56	0.23	0.07	0.69	0.11	0	0	0.16	0.01
	3	4.75	6.11	1.36	0.4	0.78	0.66	0	0	0.99	0.26
	4	4.09	4.25	0.17	0.05	0.75	0.11	0	0	0.16	0.26
Loop 4	1	3.2	3.35	0.15	0.04	0.78	0.11	0	0	0.16	0.01
	2	3.33	3.56	0.24	0.07	0.7	0.11	0	0	0.16	0.01
	3	4.89	5.9	1.01	0.3	0.84	0.99	0	0	1.49	0.33
	4	4.08	4.26	0.18	0.05	0.75	0.11	0	0	0.16	0.33
Loop 5	1	3.2	3.34	0.15	0.04	0.78	0.11	0	0	0.16	0.01
	2	3.33	3.56	0.24	0.07	0.7	0.11	0	0	0.16	0.01
	3	4.73	6.09	1.36	0.4	0.78	0.7	0	0	1.04	0.29
	4	4.08	4.26	0.18	0.05	0.75	0.11	0	0	0.16	0.29

**TABLE 3 VOLUME AFTER LOOP 5 IN PERIOD 3 (H09) (FILE: NEXTTOLL.H09.LOOP5.CSV)**

	Segments	DA_1	CV2_1	CV3_1	S2_1	S3_1	V/C
Low VOT	1	0	0	0	219	75	0.78
	2	0	0	0	145	49	0.7
	3	0	0	0	257	89	0.78
	4	0	0	0	236	78	0.75
	Segments	DA_2	CV2_2	CV3_2	S2_2	S3_2	
Med VOT	1	33	5	1	345	149	0.78
	2	0	0	0	207	89	0.7
	3	24	4	1	348	152	0.78
	4	0	0	0	272	122	0.75
	Segments	DA_3	CV2_3	CV3_3	S2_3	S3_3	
High VOT	1	231	90	3	220	129	0.78
	2	281	277	17	106	65	0.7
	3	211	91	2	207	126	0.78
	4	210	232	1	141	90	0.75

As mentioned earlier, if the max v/c ratio exceeds the threshold set by the user, tolls are incremented by a predefined factor. This is done to reduce volume in the toll segment and maintain a minimum level of service in the facility. Figure 2 shows the fluctuation of volume with the value of toll for a segment during a certain period. Increase in toll at any loop causes a decrease in the volume in the next loop and vice versa.



**FIGURE 2 CHANGE IN VOLUME WITH TOLL**





## 6.0 CONCLUSIONS

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Commented [GU8]: Summary of SACSIM toll optimization sensitivity and model specific findings.

We find that the enhancements to the SACSIM travel demand models work as intended. The introduction of value-of-time bins in skimming and assignment results in user segments whose path reflects the willingness-to-pay of each segment. In the toll optimization procedure, lower VOT bins get priced out of more congested toll segments before higher VOT bins due to increasing prices. We also find that the toll adjustment algorithm works as intended; toll segments with higher levels of demand experience higher prices as the algorithm seeks to find demand that results in a reasonable level-of-service (V/C ratio of 0.8). Toll segments with low demand experience relatively low prices, approaching the minimum price for the segment if demand is very low.

We also find that the hypothetical scenario that the project team tested (conversion of HOV lanes to High-Occupancy Toll lanes on segments of I-5 south of downtown Sacramento) resulted in very high prices. This was due to high peak hour volumes of HOVs and limited additional capacity to sell to SOVs. In such cases, the toll price increases until either the v/c ratio on the lane is at or lower than 0.8 or the toll price reaches the maximum toll set by the user. If HOV demand consumes close to 80% of the capacity, the toll price must increase until all VOT bins are priced out of the lane. Therefore it is important to consider the forecasted HOV demand when screening candidate facilities and freeway segments for HOT lane treatment.



55 Railroad Row  
White River Junction, VT 05001  
802.295.4999  
[www.rsginc.com](http://www.rsginc.com)



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