Mass-Pike Toll Plaza Simulation

A study using simulation tools for optimizing the Exit 19 Beacon Park toll plaza

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Introduction and Problem Definition

Traveling on any highway is stressful enough, but when rush hour comes around and it is necessary to be somewhere on time, every second of saved travel time counts. One cause of traffic on major highways is the presence of toll plazas. These require drivers to slow down, some stopping to pay the toll, creating a back-up that could last for miles.

Other projects were done that are similar to the one conducted here. One such project happened with the Tobin Bridge in Boston. It was decided to make all the tolls electronic, thus increasing throughput over the bridge, which serves as a major connector to the city from the north shore. Another project was done on the Golden Gate Bridge in San Francisco, California. This bridge also serves as a major connector, so officials decided to invest the money to make it an all-electronic toll system. Both projects needed to collect and analyze data to see if that would be best fit for the system, which is ultimately the goal for this project as well.

An important part of making this decision is the cost of implementing this system and what it means to revenue. In 2012, the Pennsylvania Turnpike implemented an all-electronic toll (AET) on their highway. Before that could happen, it was necessary to compare and contrast costs in doing so *(1)*. The conclusion of these comparisons was that an AET system would create 5.2 million dollars in revenue per year, as it reduces the maintenance and operation costs by approximately 33%. Saving that much money per year means that the Department of Transportation can allocate that money elsewhere (i.e. improvement of roads).

The purpose of this project is to simulate a toll plaza system to figure out what can be done to better process vehicles through it. The basis of this project is the toll plaza on the Massachusetts Turnpike (Mass Pike) at Exit 19 for eastbound vehicles. The simulated toll plaza area is shown in Figure 1. The eastbound plaza currently has 7 toll lanes with 4 of them being EZ Pass lanes and 3 being manual cash collection lanes. The scope of this project is highlighted in Figure 1. This includes a 1,150 feet length of the road before the actual toll booths. The reason for choosing this length is to eliminate the effect of the vehicles going to exit 18. The area is then divided into two sections – Approach Section and Toll Lane Section. The approach section has a length of 650 feet and this is a feeder to the toll sections. The vehicles then take to one of the fast lanes or the cash only lanes. There are 2 EZ Pass lanes on either side of the road with the three ‘cash only’ lanes in the middle. Thousands of vehicles pass through this plaza each day, and the purpose of this project is to analyze how the current system is performing and how a change to this toll lane configuration affects the performance. Three scenarios are analyzed: Do nothing, changing the number of "Cash-Only" and EZ-Pass lanes, and eliminating "Cash-Only" lanes all together.

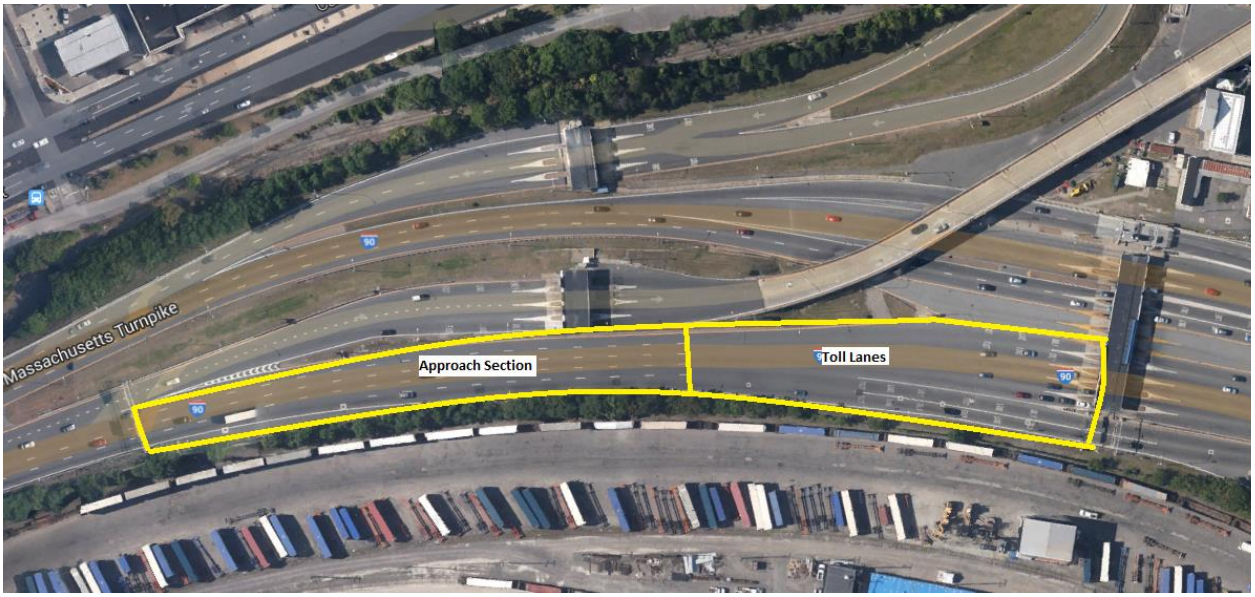

Figure 1: Toll Plaza at Exit 19 used in the current simulation

Before any simulation could take place, data was collected and sorted to be input into the system. Simulation models were built in Arena, the collected data was input and the systems were given a run length in order to simulate a real system. Different factors were then collected and organized in order to determine which system scenario would work best with this toll plaza.

Data Collection and Input Data Analysis

Arrival Data

A pivotal portion of this project was the arrival rates for the vehicles into the system. In order to make this as accurate as possible, an email was sent to an employee of the Massachusetts Toll System, who was able to send daily toll plaza counts for six months (April 2014-September 2014) as well as hourly counts for one week (June 22-June 29, 2014). Having this data, we need to find if the one week data is representative of a typical week. If the variance in the daily volumes for weekdays is too high, that will mean that using the hourly data from one week will have a higher probability of error.

An input analysis was done on the 6 months data to see the variation across different days. Only weekday and non-holiday data was chosen for this purpose as holidays and weekends had much less traffic and peak hours are almost nonexistent during these days. After filtering out the weekends and holidays, a total of 127 data points were available and they were used as data for the arena input analyzer. This data fit a normal distribution really well with a mean of 55,200 and a standard deviation of 2100. This gives a coefficient of variation of about 3.8% which show relatively low variability in the daily volumes. The results of the input analyzer are shown in Figures 2 & 3.

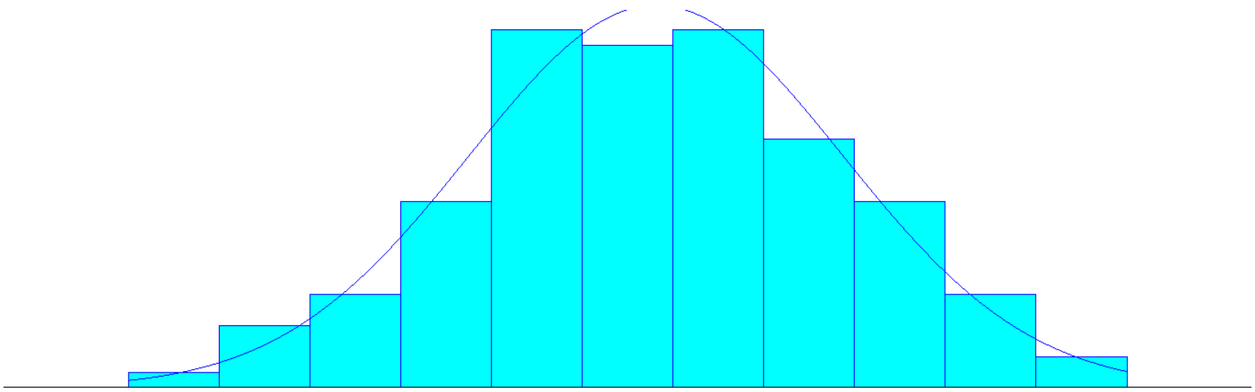

Figure 2: Histogram and Normal fit for the data

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        Distribution Summary

Distribution:   Normal
Expression:     NORM(5.52e+004, 2.1e+003)
Square Error:   0.001376

Chi Square Test
  Number of intervals   = 7
  Degrees of freedom    = 4
  Test Statistic        = 1.43
  Corresponding p-value > 0.75

Kolmogorov-Smirnov Test
  Test Statistic        = 0.0365
  Corresponding p-value > 0.15
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Figure 3: Distribution fitting summary

$$Mean\ of\ the\ daily\ weekday\ volume\ (week\ of\ June\ 23rd) = 57296$$

$$Parameters\ of\ the\ fit\ normal\ distribution = NORM(55200, 2100)$$

$$Corresponding\ Z - value = \frac{57296 - 55200}{2100} = 0.998 \cong 1$$

$$Probabilty\ that\ the\ daily\ volume\ will\ be\ higher\ than\ 57296 = P(X \geq 57296)$$
$$= P(Z \geq 1) = 1 - P(Z < 1) = 1 - 0.8413 = 15.87\%$$

This implies that according to the fitted distribution, the probability of underestimating the arrival rate (based on the June 23rd week's data) is only 15.87%. This means that the data from the week of June 23rd can be used for the model with less fear of underestimating the actual arrivals. Therefore, we have used the hourly data available to us in the simulated model without fear of underestimating the arrivals. These hourly values were input into an arrival schedule which is what the creation of entities is drawn from. The arrival pattern for weekdays and weekends is shown in Figure 4. The hourly arrival schedule used in the model is shown in Figure 5. This schedule is done for a week (168 hours) with the week starting on a Monday.

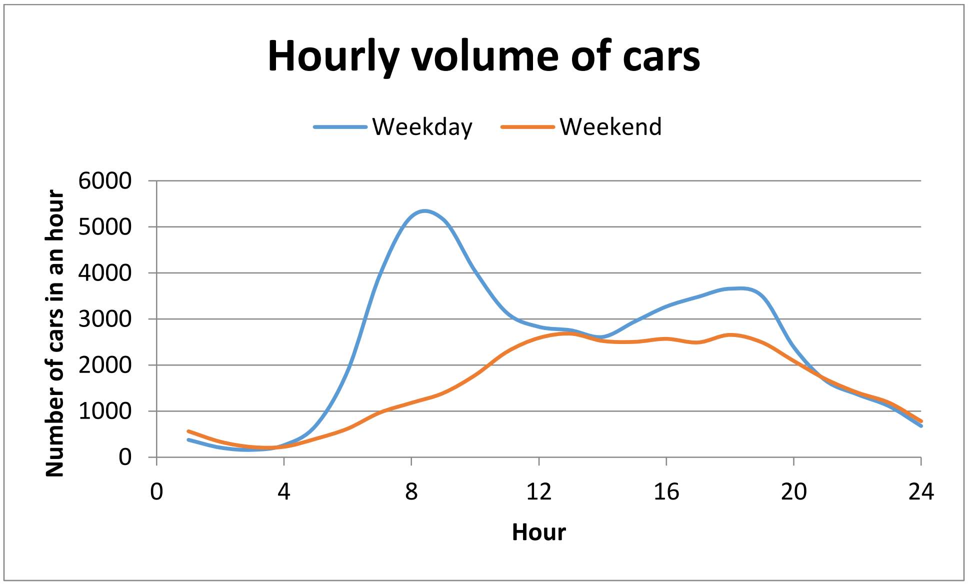

Figure 4: Arrival profiles for weekdays and weekends

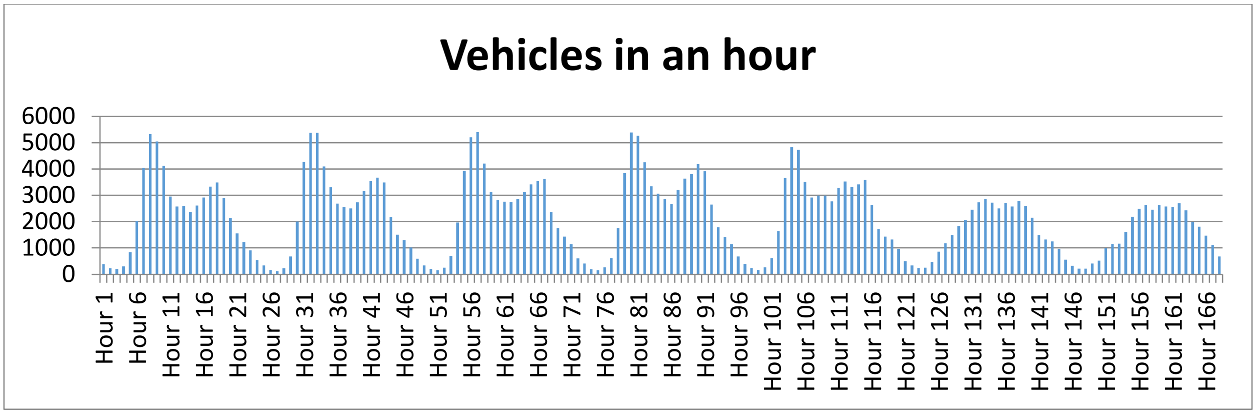

Figure 5: Schedule used for arena arrival input

Travel Times

We have two sections of road in the scope of the current simulation model. In order to compute the time in system, it is essential to calculate the travel times in each of these sections. Greenshields model for traffic flow theory was used for this purpose. Greenshields model is one of the most widely used traffic flow models and it proposes a linear relationship between speed and density. Speed in this context denotes the space mean speed which is widely used to represent the travel times on roadways and density is defined as the number of vehicles present in a given length of the road.

Density is a direct function of the space headway. Space headway is defined as the average distance between two consecutive vehicles. The relation between density and space headway is given below.

$$Density\ (k) = \frac{1}{s}; \qquad s: space\ headway$$

Space headway by its nature is dependent on the mix of the vehicles in a system. In the hourly counts obtained by MassDOT, vehicles were broken down into class: 1-9. It was then necessary to get the definition of each class of vehicle (*2*) and match it to the length of a design vehicle in AASHTO's *A Policy on the Geometric Design of Highways and Streets* (*3*). After the percentage of each type of vehicle was found, an average length was found for the vehicles on the road, which was 19.89 feet (Table 1).

Table 1: Vehicle classes and their respective lengths

	22nd	23rd	24th	25th	26th	27th	28th	29th	Total	Percent on Road	Length (ft)
Class 1	35550	50996	53075	53881	56558	53101	38524	34283	375968	0.958251	19
Class 2	288	1176	1224	1236	1254	1289	524	279	7270	0.018529	42
Class 3	275	502	495	512	506	542	306	296	3434	0.008752	55
Class 4	31	169	195	202	179	198	96	41	1111	0.002832	30
Class 5	225	749	719	716	747	715	257	230	4358	0.011107	30
Class 6	2	50	21	31	52	28	5	3	192	0.000489	25
Class 7	1	1	4	1	2	1	1	0	11	2.8E-05	45.7
Class 8	0	1	1	0	1	0	0	0	3	7.65E-06	40
Class 9	0	0	0	0	0	0	0	1	1	2.55E-06	75
	36372	**53644**	**55734**	**56579**	**59299**	**55874**	**39713**	**35133**	**392348**		

A clearance of 5 feet under congestion conditions was added to assume that vehicles would not be very close to each other to avoid crashes. This value is used to calculate the jam density of the road using the jam headway value of 25 feet. All distances for the roadway were found using GoogleMaps (*4*).

$$Jam\ density\ (k_j) = \frac{1}{s_j} = \frac{1}{25} = 0.04\frac{veh}{ft}$$

The speed-density relationship according to the Greenshields model and how the travel time is calculated is illustrated below.

$$Speed\ (u) = u_f\left(1 - \frac{k}{k_j}\right)$$

$$u_f: free\ flow\ speed\ at\ which\ the\ vehicles\ will\ be\ travelling\ when\ denisty\ is\ zero$$

$$k = denisty$$

$$k_j = jam\ density$$

Service times

The service time for the manual toll booth is based on the capacity of a manual tolling system is 498 vph with the service time distributed exponentially *(5)*. The stopping time at the toll is modelled as EXPO(7.23 seconds). The time in the toll lanes is calculated based on the approach speeds and the speed at the toll booth (EZPass -15 mph & Cash only – 0 mph). I addition to this, an additional 1 second is added for the EZ Pass lanes to account for the delay of going through the EZ Pass booth.

EZ Pass user data

An important part of this project was making sure that the number of EZ Pass users was accurate. Using the collected data, it was found that 82% of the users of toll plaza 19 on the MassPike used EZ Pass. This is real time data obtained by the Massachusetts Department of Transportation, meaning it is reliable data and not data that was made up. According the data obtained, for the entire month six month period from April to September 2014, an average of 79.6% of vehicles used EZ Pass (Table 2). This is similar to the data obtained for the simulated week, meaning the value used is warranted.

Table 2 - Percent EZ Pass for Six Months of Data, Including Total EZ Pass Percentage

Month	EZ Pass Count	Total Count	EZ Pass %
April	1178690	1460554	0.807016
May	1258886	1565358	0.804216
June	1218808	1529177	0.797035
July	1199036	1516946	0.790428
August	1171798	1502512	0.779893
September	1197532	1501146	0.797745
Total %			**0.796055**

Simulation Model

When developing the simulation models in Arena, it was necessary to try many different scenarios. The first attempt involved the use of transporters as vehicles to get the entities from the starting location to the toll booth. This proved tough to do because there were too many factors, such as the amount of vehicles in the system, which would affect the velocity of the transporter. When it was decided that transporters would not work, the next attempt used basic processes only. It was possible to create entities based on a schedule and assign those entities delay times and entity types. It was then possible to move them throughout the system using process modules and decide modules (to accommodate for resources, delay, and EZ Pass, respectively), and then record the number of transactions and then dispose of the entities (Figure 6).

The next scenario considered was a road with no cash lanes, similar to the system recently implemented on the Tobin Bridge in Boston, MA. This would eliminate all “Cash-Only” lanes and replace them with cameras that would capture either an EZ Pass or the license plate of the vehicle. The purpose of this would be to reduce congestion and increase throughput at the tolls. To do this in Arena, only EZ Pass lanes were considered, bringing the capacity to 7 (Figure 7).

The last scenario considered was looking at the “Peak Hour” traffic numbers. For this, the schedule of arrivals used in the first two scenarios was deleted, and an arrival rate was created using only the highest number of arriving vehicles per second in the last six months. The Arena model is similar to the Original model, with only the arrival rate changing (Figure 8).

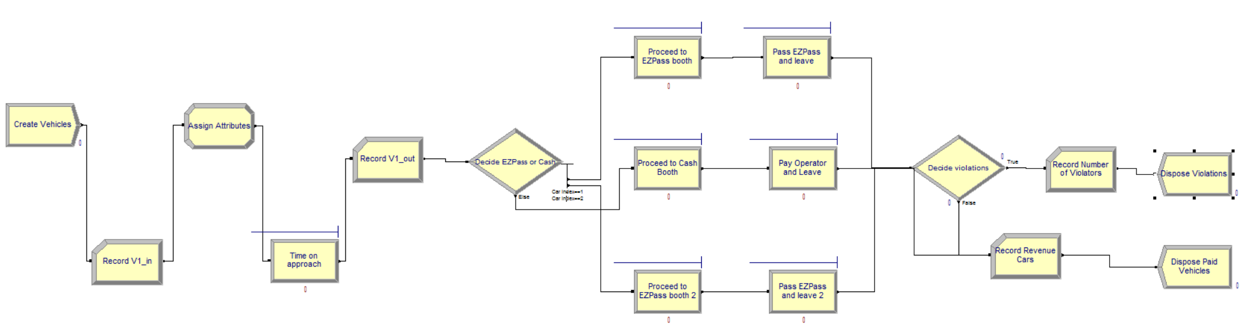

Figure 6 - Screenshot of Arena Simulation Model for Original Scenario

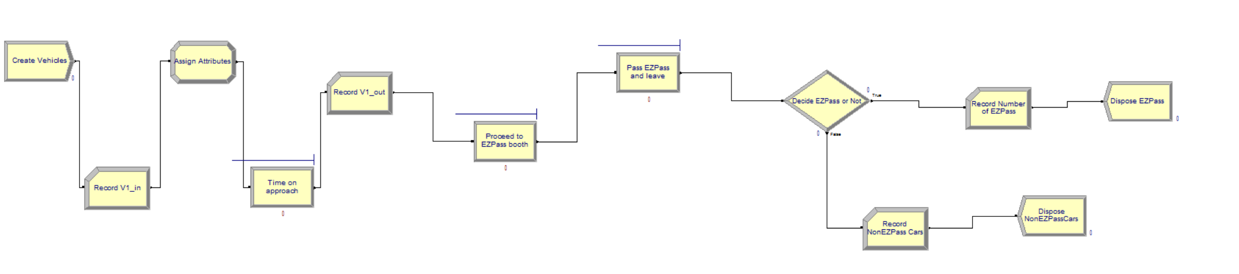

Figure 7 - Screenshot of Arena Simulation Model for "Cashless" Scenario

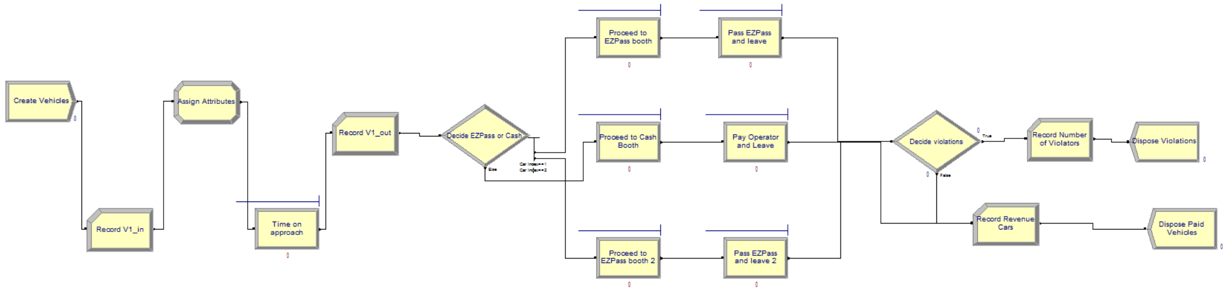

Figure 8 - Screenshot of Arena Simulation Model for "Peak Hour" Scenario

Verification and Validation

The free flow speeds used for the travel time is based on the speed limits posted for the stretch of the road. The speed limits at the toll booths (EP Pass) are also taken from MassDOT resources. The service times of the manual toll booths are taken from the field measurements done by Zarillo et al in 2000 for a toll plaza study. The arrival data is obtained from MassDOT official for the purpose of this study. The EZ Pass user percentage data is verified using the six month toll counts available through MassDOT.

To verify the validity of the current model, travel time for the road stretch using Google Maps is obtained at and peak time and at an off-peak time (Table 3). This shows that the model performs fairly well during peak traffic conditions. Both the values are slightly lower from that of the values obtained using Google Maps. This might be due to the simulated models inability to capture the lane interactions or the vehicular interaction on the road.

Table 3: Model travel times vs Google Maps times

	Model result	Google maps results	Difference
Off-Peak	40 seconds	1 minute	20 seconds
Peak Hour	1.9 minutes	2 minutes	10 seconds

Output Analysis

After running the Arena simulation models, there were important factors to analyze to which scenario was best for both the user and the agency. The performance measures used for the current analysis are the total time in the system and the cost to users and the agency (DOT). The scenarios considered are the current toll plaza configuration (4 EZ Pass + 3 Cash only lanes) and making the system All Electronic Tolls (AET) at different systems. Another scenario is also analyzed for peak hour volumes under a constrained manual toll lane (with one of the cash only booths out of commission)

Time in System

When the Arena simulation model that was originally created was ran for a run length of 7 days, many different statistics were found. One of the more important statistics was the total time in system for the vehicles. This is important to determine because it tells how long it takes a vehicle to get from one end of the system to the other, and gives a base case for comparison later on. It was found that vehicles using the cash lanes were in the system an average of 38.8 seconds while those who paid with EZ Pass were only in the system an average of 26.5 seconds (Table 4). Although many more vehicles use EZ Pass on a daily basis, the fact that they do not have to stop and pay a toll means that they can be processed through the system quicker with less delay to the traveler.

Table 4: Time in system for the two types of vehicles

	Average time (secs)	Minimum time (secs)	Maximum time (secs)
Cash lanes	38.754	27.624	111
EZ Pass lanes	26.46	24.114	36.33

During the peak hour, it was estimated that 5500 vehicles would pass through the tolls during each hour. In addition to running this simulation, Process Analyzer was used to see what happens when the number of “Cash-Only” lanes was reduced during the peak hour. It was found that the total time in the system was three-times more with only one less “Cash-Only” lane in operation (Table 5). During peak hours, when the amount of vehicles in the system is greater, it is beneficial to have multiple “Cash-Only” lanes open to increase flow through the toll plaza and decrease delay for the vehicles. The process analyzer output is shown in Table 6 and it can be observed that reducing the cash lanes crippled the traffic while the EZ Pass traffic was not affected.

Table 5: Comparison of peak traffic and over all traffic scenarios

Time in seconds	Over a week	Peak traffic	Peak traffic (1 cash lane closed)
Cash lanes	38.754	45.1	131.76
EZ Pass lanes	26.46	29	29

Table 6: Process analyzer output under lane closure

	Scenario Properties				Controls			Responses		
	S	Name	Program File	Reps	EZP_2_4	CashOnly_6_8_10	EZP_12_14	Car_CashOnly.TotalTime	Car_EZP_1.TotalTime	Car_EZP_2.TotalTime
1		Scenario 1	6 : TollPlaza	1	2.0000	3.0000	2.0000	0.754	0.484	0.484
2		Scenario 2	6 : TollPlaza	1	2.0000	2.0000	2.0000	2.196	0.483	0.483

In order to see whether or not an all-electronic toll (AET) system would be beneficial (no cash transactions), a separate model was constructed in Arena and data was collected. The model was run for three different speed limits for the fast lanes (15, 25, 30 and free flow speed) and the total time in system is shown in Table 7. It can be clearly seen that moving to an All Electronic Toll (AET) system helps reduce delays in the traffic. Having to stop and pay tolls is a big reason for delay on highways, and getting rid of this process will help increase throughput and decrease delay.

Table 7: AET system times under various speeds

	Average time (secs)	Minimum time (secs)	Maximum time (secs)
AET (15mph)	26.45	24.11	34.99
AET (25 mph)	24.25	22.22	31.27
AET (30mph)	23.45	21.52	34.61
AET (free flow)	22.56	20.25	32.47

Costs

This is an important factor as we will be considering costs to both users and the Toll plaza operation agency. The total time needs to be calculated to calculate the costs associated with users being delayed on the highway. The total times for a period of one week for different scenarios are given in Table 8. This is based on the number of entities processed by the arena model and their average time in system. The total time for each scenario is calculated based on the following equation.

$$Total\ Time = \sum_{Vehiicle\ type} TiS * Number\ of\ users$$

Table 8: Total time in system for various scenarios per week

		TiS (avg) in secs	# of users	Total Time per week (hours)
Current system	Cash	38.75	65,478.24	704.87
	EZP	26.46	298,289.76	2,192.43
AET (15mph)	Non-EZP	26.45	65,464.74	480.98
	EZP	26.45	298,228.26	2,191.15
AET (25mph)	Non-EZP	24.25	65,489.04	441.14
	EZP	24.25	298,338.96	2,009.64
AET (30mph)	Non-EZP	23.45	65,551.50	427.00
	EZP	23.45	298,623.50	1,945.20
AET (free flow)	Non-EZP	22.56	65,379.06	409.71
	EZP	22.56	297,837.94	1,866.45

For the user, it is important, especially during the morning commute, to arrive at their destination on time. On average, a worker in Massachusetts earns $27.12 per hour *(6)*. In order to get the delay cost to each user in the system, the following equation was used

$$User\ Delay\ Cost = Total\ Time * Hourly\ Wage * Occupancy\ of\ the\ vehicle$$

The average occupancy of the vehicle is assumed to have been 1.5 passengers per vehicle *(7)*. Using the above equation, the total delay cost to the user under different scenarios for one week duration is shown in Table 9.

Table 9: User delay costs per week

	Total Time (hours per week)	User costs (per week)
Current system	2,897.30	$ 117,862.29
AET (15mph)	2,672.13	$ 108,702.38
AET (25mph)	2,450.79	$ 99,697.97
AET (30mph)	2,372.20	$ 96,500.91
AET (free flow)	2,276.16	$ 92,594.18

The other important costs associated with this are the costs to the agency and the revenue generated by the tolls. Cost to the agency is the salaries paid to the toll plaza employees. There are other maintenance costs associated with this but they are going to be almost the same for all the scenarios under consideration and hence, are not considered in this study. The salary of the toll employees is given by the following equation. The average hourly wage for toll operators is $14/hour.

$$Salaries = Hours\ of\ operation * Hourly\ wage * N_{cash\ booths}$$

The toll revenue is given by the following equation.

$$Toll\ Revenue = \sum Toll\ rate * (N_{users} - N_{violations})$$

The Toll rate under the current system is $1.25 for all types of users. The number of violations under the current system is about 1.394% of the total number of users. This number is based on the MassDOT data used for this study. For the AET scenario, the Toll rate is assumed to be $1.25 for the EZ Pass users and $1.50 for the Non-EZ Pass users. This is based on the current toll system being adopted on the Tobin bridge tolls. The extra cost for the non-EZ pass users is to offset the costs of operating the license plate recognition system which will be adopted in the AET system. The weekly salary cost and the toll revenue for each scenario is given in Table 10.

Table 10: Agency costs and revenue per week

		Toll Revenue per week		Salary per week
Current system	Cash	$ 81,847.80	$ 448,371.34	$ 7,056.00
	EZP	$ 366,523.54		
AET (15mph)	Non-EZP	$ 98,197.11	$ 470,982.44	N/A
	EZP	$ 372,785.33		
AET (25mph)	Non-EZP	$ 98,233.56	$ 471,157.26	N/A
	EZP	$ 372,923.70		
AET (30mph)	Non-EZP	$ 98,327.25	$ 471,606.63	N/A
	EZP	$ 373,279.38		
AET (free flow)	Non-EZP	$ 98,068.59	$ 470,366.02	N/A
	EZP	$ 372,297.43		

The cost savings experience because of reduction in the delays from the current system to the various options of the AET is illustrated in the chart below. The costs in the chart represent annual costs in USD.

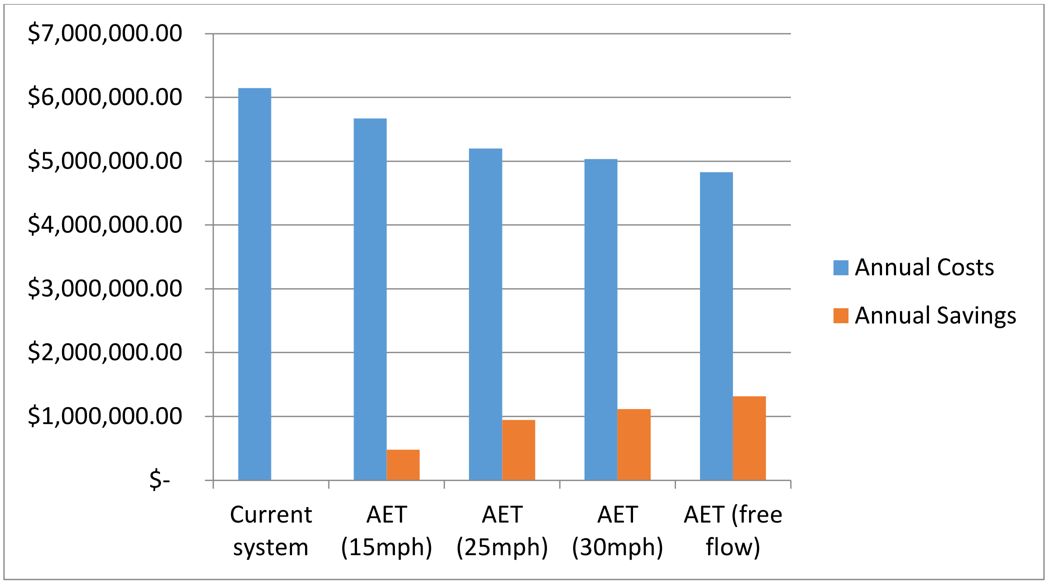

Figure 9: Annual delay costs and saving for the users

Conclusion

With the current system in place, the agency makes a certain amount of revenue. However, if there were to be changes to an all-electronic tolling system (AET), the users would benefit as well because of the amount of savings that would occur. The following is what the users would save with a new AET system: Speeds at 15mph - $477,623.53, Speeds at 25mph - $947,139.43, Speeds at 30mph - $1,113,843.03, and Speeds at Free Flow - $1,317,551.05. From this, it seems clear that the agency should implement an AET at Free Flow speed because of how beneficial it would be to users. But doing that requires money that the state may not have.

Another factor is the time in system per vehicle. With the current system, a vehicle spends an average of 38.8 seconds if they are paying with cash and 24.5 seconds if they are paying with EZ Pass. When an AET system is implemented, these total times decrease as the speed increases. At a speed of 25mph, the vehicles spend an average of 24.25 seconds in the system. At a speed of 30mph, vehicles spend an average of 23.45 seconds in the system. At free flow speed, vehicles spend an average of 22.56 seconds in the system. Coupled with the annual savings to the user, it is clear that implementing an AET system at free flow speed would be most beneficial, but it may not be feasible.

It is not very expensive to switch from the current system to and AET with speeds at 15 miles per hour because of the current lane width and other existing infrastructure. However, increasing speed will make it necessary to increase the lane width and also make sure any overhangs still provide sufficient stopping sight distance in case there is traffic downstream.

Some drawbacks of the simulation would be the fact that cross-lane interactions are not captured. Also, there was no input for accidents or extreme weather that could also cause delays within the system. After running the simulations and analyzing the data, it is recommend to implement an AET with a toll speed of 15 miles per hour because minimal changes are needed to the current infrastructure. However, if there were enough money allocated, it is recommended that the state implement an AET at the current speed of 40 miles per hour because of cost savings and revenue.

Overall, agency and revenue do not change by a significant amount to necessitate a change right away. However, over the cost of a few years, as the number of vehicles continues to increase, it may be worth it for the Massachusetts Department of Transportation to make these changes to increase their revenue and further decrease delay to all vehicles.

References

1. Pennsylvania Turnpike Commision (PTC), *All-Electronic Tolling Feasability Report,* https://www.paturnpike.com/aet_public/pdfs/AET_Feasibility_Report_printable.pdf, Accessed December 5, 2014
2. Massachusetts Department of Transportation, *Toll Calculator*, http://www.massdot.state.ma.us/highway/TollCalculator.aspx, Accessed December 5, 2014
3. American Association of State Highway and Transportation Officials, *A Policy on Geometric Design of Streets and Highways,* http://design.transportation.org/Documents/TurnRadii,GreenBook2004.pdf, Accessed December 4, 2014
4. www.google.com/maps , Accessed December 6, 2014
5. Zarrillo M.L. Capacity Calculations for Two Toll Facilities: Two Experiences in ETC Implementation, University of Massachusetts Dartmouth, January 2000.
6. Bureau of Labor Statistics, *May 2013 State Occupational Employment and Wage Estimates for Massachusetts*, http://www.bls.gov/oes/current/oes_ma.htm#00-0000, Accessed December 6, 2014
7. NHTS, *Average Vehicle Occupancy*, http://www.transpoplanner.com/wp-content/uploads/2013/03/tumblr_inline_mguth6JGt81re4ckx1.jpg, Accessed December 9, 2014