International Journal of Engineering, Management, Humanities and Social Sciences Paradigms (IJEMHS)
Volume 30, Issue 03, Quarter 03 (July-August-September 2018)
An Indexed and Referred Journal with Impact Factor: 2.75
ISSN (Online): 2347-601X
www.ijemhs.com

Design of Toll Plaza using a Coupled Multiple Queue Multiple Server Queuing Model

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Publishing Date: July 12, 2018

Abstract

Toll plaza operation is a critical component of roadway operations throughout the country, as tools provide both revenue for expansions and opportunities for demand management. Electronic tolling has introduced a new form of driver decision making at toll plaza due to the additional payment. Describe the user convince marking at toll plaza due to the additional payment. Recommendation for future research include to examine traffic flow and safety impact at toll plaza under varying traffic condition and demand with open road tolling lanes strategies. Developing enhancements to vision to address parameters limitation associated with discrete choice modeling at toll plaza. Multi-server queuing analysis can be used to estimate average time and queue length at toll plaza and parking exit plazas giver arrival rates, number of services, and services rates. After discussing the natural behavior of traffic and making a few reasonable assumptions to simplify traffic streams in toll plazas, we break the travel process in toll plazas into two stages: Toll collection and Margins. We apply queuing theory to each stage, modeling each stage as a queuing system. Having determined that an optimal toll plazas minimizes travel time, we derive a formula to calculate the average wasted time per driver in terms of number of incoming lanes, traffic flow and number of toll booths.

Keywords: *Queuing Model, Toll Plaza, Coupled.*

Overview and Problem Statement

Toll financing has been used throughout the history of civilization to make the building of long-distance roads possible. Toll roads in Asia were known to ancient Greek writers in antiquity. The first turnpikes in America were built in the 1790s and helped to open the Midwest to settlement. Beginning in the 1940s, America's first modern freeways were financed with tolls, paving the way to the Interstate system Americans now enjoy. Today developing nations such as China are building their own networks of superhighways, and they too are turning to the tollbooth to foot the bill. As the congestion and pollution from too many cars on the streets become an increasing concern in many cities, another benefit of tolling has revealed itself: Tolls are being used successfully in places such as Singapore and London not just to finance road construction, but to limit the flow of vehicles into the urban core, increasing transit usage and unclogging the crowded streets.

The emergence of ETC has resulted in an array of challenges at toll plazas in the United States. The introduction of electronic toll collection has become increasingly widespread at tolling facilities throughout the United States as a result of documented benefits associated with its implementation. Toll operators laud ETC's efficiency, accuracy and cost effectiveness, while consumers enjoy the convenience and ease of use (9). Investments in ETC often have short return on investment periods due to their low cost per transaction and high levels of lane throughput. The advent of ETC lanes prompted agencies to slowly migrate more lanes over to this technology. Despite the user convenience, these facilities have introduced some additional challenges. Confusion at the toll plaza, difficult merging scenarios, and the unexpected behavior has actually increased certain crash patterns at toll plazas (4).

Mixed use lanes, express lanes, and dedicated lanes vary from tolling agency to tolling agency with no standardization as to which lanes allow certain types of traffic (2). Toll plazas are often situated at the junction point of major arterials and highways where

accidents and queues pose major safety and congestion concerns. Despite this challenge, research quantifying the various aspects of toll plaza operations and safety has been somewhat limited in scope. The history of ETC implementation occurred on a trial and error basis by tolling agencies, and while "lessons learned" have been shared, standardization remains deficient. More specifically, there is a need to expand upon existing research to further quantify the related impacts associated with toll plaza configurations. There is a need for research that explains how the use of different lane configurations, number of lanes, and placement of lanes affects both safety and operations in or around toll plazas. The research documented herein was developed to identify a methodology for identifying the root cause of safety issues at toll plazas by evaluating field work data coupled with elements of driver decision making processes from laboratory experiments. Furthermore, the research attempted to model driver behavior at toll plazas and to investigate the operational aspects through field observation.

Literature Review

The toll plaza environment is in many regards one of more complex and demanding places to drive in terms of safety and motorist involvement. Vehicles approach at high speeds and decelerate at various speeds while merging and scanning for signage and toll lanes. In order to understand the intricacies of toll plaza operations, a review of current and past literature was compiled. Studies highlight driver decision making, signage, lighting give light to the vast amounts of sensory information and methods of payment. Simulation efforts with ETC equipped toll environments have revealed the theoretical performance and introduced behavior models to hopes to replicate and predict real world events. The following background is by no means an all-encompassing review electronic tolling safety and simulation but should provide a backdrop for the research proposed herein.

Contrastingly, a 2007 report of the New York State Thruway Authority crash records showed an increase in ETC related crashes as ETC penetration increased from 1992 to 1998 (11). Crashes on an Orlando Florida expressway doubled after installing dedicated ETC lanes. The crash rates involving dedicated ETC lanes and/or ETC vehicles rose from 3.375 crashes per month to 7.5 crashes per month. At the same toll facility, rear-end crashes increased as a result of a adding a dedicated ETC lane. Not even a year later a second adjacent ETC lane was installed, and again rear-end crash frequency increased. Speed was the leading cause of conflict and the culprit in raised accident rates. Prior to toll plaza renovations speed variance was low, but after construction velocities noticeably escalated (4). These results provide strong support to the idea that decision making spurred by ETC lanes may spark conflicts at toll plazas that are leading to additional accident.

Another model, TPSIM, built by Correa et al. (2004) was able to reproduce typical toll plaza operations with lane decision based on queue length (14).
The deterministic toll plaza software SHAKER created by Florida Department of Transportation out puted most efficient plaza configurations by assigning approaching traffic to shortest queue lanes (15). TOLLSIM toll plaza model, developed by Wilbur Smith, now CDM Smith, estimates traffic characteristics such as delay and queues at a plaza (14).
Few studies have developed toll plaza micro simulations with widely available traffic simulation programs (AIMSUN, VISSIM, Paramics, CORSIM). The model produced by Mudigonda et al. (2008) revolves around maximizing user utility based on three parameters for ramp plazas was programmed into an API by Nezamuddin (16). The model validated mainline plazas on Orlando Orange County Expressway Authority (OOCEA) toll facilities. The study found success in modeling field observations with correlating lane assignments on the order of 0.98 (3).
Fuller et al. worked with CORSIM developers to add a toll plaza module to CORSIM version 6.3 (17). CORSIM models in the past had used Stop and Yield Signs to emulate cash and manual payments. Previous attempts at modeling were deterministic and used shortest queue for lane determination.

Experimental Data Analysis and Results

Conflict and Event Study Notes

The conflict and event study supplemented the field data collection the micro simulation model development. Utilizing practices from FHWA's observers guide to Traffic Conflict techniques, a

review of safety and operations was conducted at the West Springfield I-90 toll plaza .

Conflicts vary depending on origination of vehicles competing for the same roadway space. For the purpose of this research, same direction conflicts were nearly exclusively studied. While opposing conflicts may occur, their risk at exit and entrance plazas in Massachusetts is mitigated by stanchions, cones, low speeds and center lane closures. Pedestrian conflicts from toll plaza employees do occur from time to time but authorities limit exposure to this risk through training.

Same direction conflicts in toll plazas are primarily related to lane-changing events. In these instances, the overtaken vehicle is in danger of rear ending or sideswiping the provoking vehicle. The result of conflict may lead to a secondary conflict where a following or nearby vehicle may have to decelerate, maneuver unevenly to avoid a collision. Secondary conflicts commonly appear as a more relaxed deceleration. While a secondary conflict may seem to trigger a tertiary conflict, no such term exists.

Table 1: Conflict and Even Register

Conflict and Even Register	
Abrupt stop	1 per hour
Evasive Maneuver	4 per hour
Car Honking	9 per hour
Swerving	1 per hour
Secondary braking	7 per hour

Crash Analyses

Crash analyses were performed on crashes occurring in the Commonwealth of Massachusetts from January 2010 through December 2012. All crash figures were linked geographically to toll plazas on the basis of proximity and contributing role in the collision. All toll plazas, mainline and entrance and exiting were considered for inclusion regardless of whether there was a transaction or just a “ticket” or digital “ticket” issued for interstate entrance. Traffic count data from MassDOT contained transactional toll records of exiting vehicles; therefore crash rates were based on the dataset of crashes exclusive of entering vehicles. All other plazas including mainline plazas, tunnels, and bridge facilities contained all toll crashes.

Crash Level Trends

The preliminary round of trend analysis looked at several isolated crash attributes. In order to identify complex multi-attribute relationships, single variables were first considered to explain the nature of crashes at toll plazas.

Crash Rate per Plaza

Crash rates were normalized and based upon a million entering vehicles. Annual average daily traffic (AADT) information needed for these calculations was derived from 2012 MassDOT plaza transaction records. The highest crash rate plaza for the three year analysis period was interchange 14 at the intersection of I-95 at 1.98 crashes per million entering vehicles. Additionally, interchange 18 in Allston had the second highest rate with 1.62 crashes per million entering vehicles. These rates are well above the statewide rates of 0.55 for urban interstates (33).

Time of Day

Time of collision was another factor investigated to improve understanding into crash causation. Crashes were categorized into time period buckets for analysis. Most toll plaza collisions occurred during normal commuting hours. During the afternoon commuting period, 2PM – 6PM, there were 101 crashes at toll plazas.

Table 2: Time of Day Crash Results

Time	2013	2014	2015	Total
6m-10am	37	34	43	114
10am-2pm	13	26	23	62
2pm-6pm	35	33	33	101
6pm-10pm	19	19	29	67
10pm-2am	6	13	5	24
2am-6am	3	7	3	13

Injury Status

The majority of crashes at toll plazas have a non-injury outcome. No fatal crashes were reported during the analysis period from 2010-2012; however they have occurred in recent years. Very few crashes result in serious injury as indicated by the incapacitation level found crash category included injury statuses labeled "not reported" and "unavailable" information.

Table 3: Injury Status Crash Results

Injury status	2013	2014	2015	Total
No injury	96	105	101	302
Non-fatal injury	13	21	17	51
Non-fatal injury- incapacitating	1	1	1	3
Non-fatal injury-non capacitating	5	6	10	21
Non-fatal injury-possible	7	14	6	27
Unknown	4	6	18	28

Age

Raw results are presented strictly by quantity per age group and then again in the form of normalized rates from licensed records. Massachusetts driving population records from 2008 were used to normalize crash rates based on number of licensed drivers in each age range. Quantity based age groups failed to shed light on groups at risk properly. The normalized data below shows representative crash rates per 100,000 licensed drivers in the Commonwealth of Massachusetts. The age range 20-39 years held the highest rates and subsequently was analyzed further in to identify any particular age or time period in a young drivers' life that may particularly be of risk.

Conclusions

Although the completed research provided significant insight on varied toll plaza operation and safety, additional research questions remain. Completion of thesis tasks resulted in several recommendations on where to expand research of these highway environments. Integration of a driving simulator would be a logical next step to evaluate driver decision making for several reasons. Eye trackers are one feature of most modern driving simulators, which provide visual insight into driving behavior. While drivers approach plazas they tend to scan for signage, other vehicles on their route to an optimal lane by weighing lane changes to queues and payment

methods. By gauging human factor trends and time spent on these tasks, engineers could better design toll facilities. The VISSIM model developed as part of this thesis effort utilizes many aspects of the microsimulation software, but could be improved for wider applicability. The addition of varying traffic conditions and demand, and open road tolling lanes would allow this model to simulate most toll plazas in existence today. The microsimulation model had parameter limitations of the discrete choice model. Future research would involve programming an application programming interface (API). A programmed driver decision model could be easily modified to add driver parameters as research in the toll environment expanded.

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