PREDICTION OF CONGESTIONS USING BASIC TRAFFIC UNIT

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ABSTRACT

In any form of traffic, whether it is physical or digital, the main problem that sparks a lot of interest for researchers is congestion. This paper discusses a study of congestion around toll plazas. A newly formulated model called Basic Traffic Unit (BTU) is introduced from previous research. BTU is a representation of a basic network connected to form a larger network. A simulation study is conducted and some queuing theories are applied to calculate the measure of performance. Two sets of data from different modes of toll payment are collected. The same two types of payments are simulated and the measure of performance is recorded. The two types of payments from the collected real data are used to calculate the measure of performance using the formula developed by the BTU. This study demonstrates that the results from simulated data can be used to compare with the results from the real-time data using the formula developed by a static model of BTU to predict possible congestions. Comparing results from both methods validates the claim that BTU is useful for predicting congestions.

Keywords: Traffic, congestion, simulation, static, toll plaza

1.0 INTRODUCTION

Traffic is a movement of humans, vehicles, ships, messages, signals, etc., in communication systems, highways, water routes, paths, etc. Traffic congestions or traffic jams are said to occur when traffic becomes slow and below its normal speed or comes to a complete stop, results in longer trip times, or an increase in numbers in queues. [1] conducted a study to measure the intensity of traffic congestion using traffic volume survey and spot speed study. One way flow has been suggested to some part of the city. [2] gave an overview of diferent traffic congestion detection methodologies and scopes. The motive of the study is to promote smart transportation in developing countries. [3] believes that in order to reduce traffic congestion, both strategies of improving road capacities and public transport and physical planning should be applied together. [4] reviewed economic principles behind congestion pricing in static and dynamic settings. They considered the implications of congestion pricing for optimal road capacity and offered social and political resistance to road pricing. The growing usage of artificial intelligence (AI) can speed up the predicting and overcoming traffic congestion problems. [5] summarized the strengths and weaknesses of various existing research methodologies of AI. [6] reviewed various aspects of traffic congestion problems and believes that Intelligent Transport System (ITS) will improve the current state of transportation.

Some researchers believe that congestions begin from toll plazas [7], [8], [9], and some researchers had proposed an efficient algorithm to improve traveling time [10], [11], [12]. [13] studied the road inventory, traffic volume, space mean speed, arrival rate, time headway and service rate in order to analyse the performance of a toll booth. Their flow theory diagram exhibited that as the density increases the effective speed decreases on the toll plaza section. [14] predicted that gridlock situations will occur in a few years time and proposed an intelligent transport system to be implemented. The intelligent transport system is the automated E toll system. Techniques of toll collection do play an important role in causing traffic congestion problems. From all the review papers and from different researchers, we conclude that a model should be introduced to detect congestion around toll plazas.

This paper focuses on congestions around toll plazas. In our previous research, we had introduced a new model called Basic Traffic Unit [15]. The Basic Traffic Unit is formulated to predict possible traffic congestions at toll plazas. From the measureable results of queuing theory and the BTU model, it can be concluded that the new model can be used strategically for planning toll plazas and for predicting possible congestions. The Basic Traffic Unit (BTU) can also be adopted even for complex networks.

2.0 LITERATURE REVIEW

Tolls are often needed to collect fees to help finance the completed construction and for maintenance of long distance roads. Toll plazas consist of a row of toll booths and they are erected all over the country. The amount of toll varies for different types of vehicles, and the modes of payment can be as cash or via an electronic payment system. In Malaysia, there are mainly two types of electronic payment. One is called Touch‘nGo, where a certain amount is deducted via a credit card-sized plastic card embedded with a Philips’ MIFARE Classic microchip technology when it is touched at a receptor device at a toll plaza [16]. The other mode of payment is called SmartTAG, which is a vehicle on-board unit that works in combination with the Touch‘nGo card. It is a battery-operated electronic device that receives and transmits the information between the Touch‘nGo card and the tolling system at a toll plaza [17].

A toll plaza can typically be divided into five distinct zones, as given in Fig. 1. Traffic approaches the toll plaza through a point A. Point B is where the traffic enters the area known as the Queuing Area, where temporary queues may build up (a funnel effect). At point C, the diagram shows a number of toll booths. Once payment is made, the traffic will move out of the toll booths towards point D into another possible hold up area, known as the Merging Area (a bottleneck effect). Finally, the traffic moves through point E to reform the original highway. Solutions proposed for congestions at toll plazas will have to deal with at least three areas of concern vis-à-vis the traffic flow and/or the toll plaza configuration:

- Volume of traffic arriving at the Queuing Area (queuing models);
- Arrangement of the toll payment types of the Toll Booths (lane changing and toll booth type models);
- Control of the volume of exit at the Merging Area (queuing models).

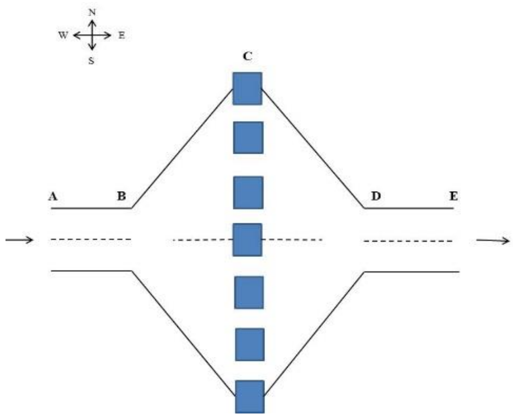

Fig 1**:** A toll plaza divided into five components

The approaches used may be based on some of the following with a view of understanding the situation as well as to propose possible solutions: Modelling the situation at the Queuing Area, Toll Booth configuration (types), Merging Area, Queuing Theory, Simulation, Optimization, etc.

There is a necessity to examine the performance of a system which delivers services, when rising demands randomly occur. A model in queuing theory is designed so that the listed sub-system of queuing can be identified, such as: arrival process - singly or in a group, inter-arrival time distribution, finite or infinite number of customers (vehicles); service mechanisms – service time distribution, number of servers (toll booths), number of stages; queue characteristics - queue discipline (FIFO, LIFO, RANDOM), system capacity. Queuing theory evaluates delays in a given section from one location to another location by using cumulative curves [18], studying the parameters involved, including sensitivity analysis and environmental impact [19].

Computer simulation is used to help better planning, designing, developing, demonstrating and operating traffic systems. In simulation, analytic tools are used to make the problem more detailed to be compared with the theoretical model. The computational analysis will compare the results from the simulated model with the results from the theoretical algorithm [20]. Due to the complexity and the growing size of applications of simulation, new programming techniques such as object-oriented programming and virtual reality tools are commonly used. The latest trends in traffic Systems simulation use GIS databases with some programs and applications of parallel computing [21]. Combining the use of operations research techniques such as queuing theory and simulation will generate more realistic results. [22] indicates that there are about 40 (queuing) models associated with different queue management goals and service conditions. If one does not have a strong knowledge in operations research, it is easy to apply a wrong model. [23] claimed that some percentages of heavy vehicles in traffic flow significantly effects queue lengths at toll plazas and confirmed that part of the cause of traffic jams are contributed by toll plazas. In order to ease the amount of time spent at a toll plaza, an automation of billing collection systems were suggested [24]. [25] studied a reversible lane concept for the collection of toll according to demand. Simulation was performed using an M/M/1 queue model, which clearly agreed with the results, with each toll booth being represented as one server. [26] claimed that toll booth capacity and type of service have influence on traffic operations and the efficiency of the toll plaza. [27] developed an optimization algorithm to provide better lane allocation in front of a toll plaza. A camera based traffic measured traffic state, which would then shift vehicles to lower congested lanes based on queue lengths per lane. All these findings contributed to the study to identify and to reduce traffic congestions.

3.0 BASIC MODEL FOR TRAFFIC SYSTEMS (BTU)

There is clearly an essential need to properly make traffic congestions easier to understand in a more formal way, perhaps in the specific form of a standard model for traffic systems in familiar terms of basic traffic units that can be uniquely combined into a network. The standard model should be capable of explaining observed congestions as well as to predict possible congestions. The Basic Traffic Unit (BTU) model in Fig 2 is adapted from [28]. BTU can represent the toll plaza area, junctions, exits, merging areas, parking lots, checkpoints (police), etc. Basically, it can take any relevant problem and represent it as a network. As a static model, BTU will be able to calculate the amount of flow a network can maximally take before a congestion occurs. Since BTU is a model to predict congestions, for this paper, we will consider the bulk arrival of vehicles. BTU can assist in planning a proper new toll plaza by predicting possible congestions using a simulation technique.

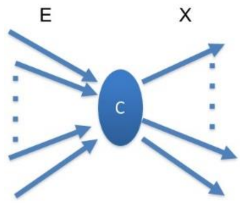

Fig 2: A Basic Traffic Unit is a triple *(C, E, X)*

Fig. 2 shows a central point C, where all roads in the unit meet. C can represent a toll booth (or a set of toll booths) in this case. $|E|$ is set of roads entering C and $|X|$ is a set of roads leaving C.

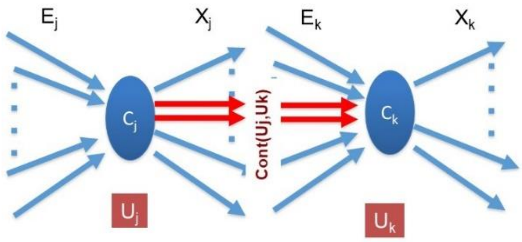

Fig 3: Traffic System

From Fig. 3, the combination of BTUs represents a traffic system. From the definition above, if $|E| > |X|$, it is called a **Bottleneck**, if $|E| < |X|$, it is called a **Funnel,** and if $|E| = |X|$, it is defined as a **Straight**. A **traffic system** consists of interconnecting sets of BTUs, which are represented by sets of triples $U_j = (C_j, E_j, X_j)$ that are adjacent to and **precedes** $U_k = (C_k, E_k, X_k)$ if the intersection (X_j, E_k) is not empty. We define a **continuing point** $Cont(U_j, U_k)$ as a situation where there are meeting points of exit roads X_j and the entry roads E_k occurring. $Cont(U_j, U_k)$ is reffered to as **derived bottleneck** if $|X_j| > |E_k|$.

3.1 Example

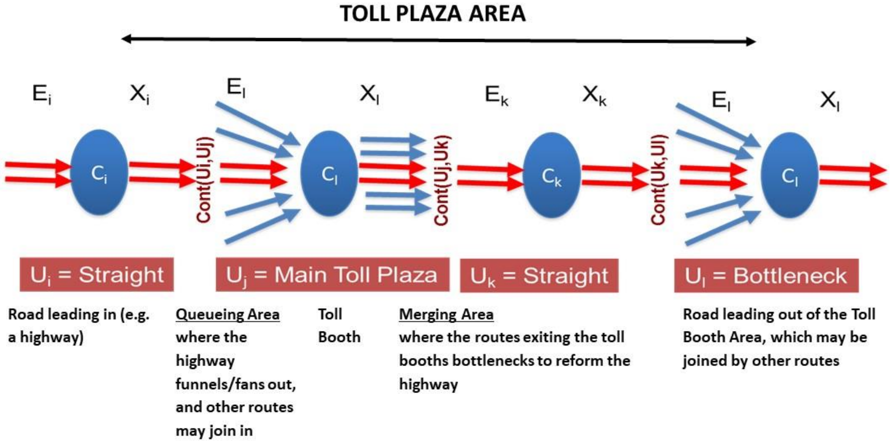

Fig 4: A Representation of Toll Plaza Area Using BTU

Fig. 4 presents four adjacent sets of triples U_i, U_j, U_k, U_l that form a full Toll Plaza area. U_i is a **straight** moving towards the Toll Plaza area. U_j is the main Toll Plaza, where C_j is the toll booth. $Cont(U_i, U_j)$ shows the point where traffic from a **straight** joined by possible traffic from other sources in a form of a **funnel** moving to the queueing area, E_j. X_j is a merging area where the routes exiting the toll booths **bottleneck** to reform the highway. A **straight** U_k is part of the merging area, and after that U_l, which is a **bottleneck**, exhibits the road leading out of the Toll Plaza area, which may be joined by other routes. While C_j represents the toll booth, C_i, C_k, and C_l are simply virtual points. The last BTU, C_l serves as a point where all these traffic combine into a smaller number of road lanes. The other sources of traffic which join up with the traffic from the toll plaza will cause a **bottleneck** at this point. If the distance is very short from $Cont(U_j, U_k)$ and U_l, where bottlenecks are clearly shown, congestion problems will obviously develop.

3.2 CLEARANCE TIME

Clearance time is needed to determine how long a motorized vehicle needs to spend at a toll booth and in a toll plaza before it can continue with its intended journey. We developed formula for clearance time at toll plazas as well as clearance time at a junction. The proper interpretations is adapted from [15].

In order to give an idea of overall congestion time, we need to measure the time to clear the BTU and later the traffic system. In other words, we are interested to know the average maximum clearance time which is the same as the average time in the system as in Queueing Theory. Given a basic traffic unit (C, E, X). Let t be the time to clear C. In this case, it is the time to pay at the toll booth, or simply the time to clear a junction. Clearing one toll booth is the same concept as in the M/M/1 model in Queueing Theory. So, having more than one toll booth means that we need more than one BTU arranged in parallel order. The number of exit lanes $|X|$ does not contribute, as C can only process one vehicle at a time. The number of entry lanes $|E|$ also does not contribute for the same reason, but rather the key is the number arriving at C, say n, which would then bunch up at the queueing area if $n \geq 2$ within the time t.

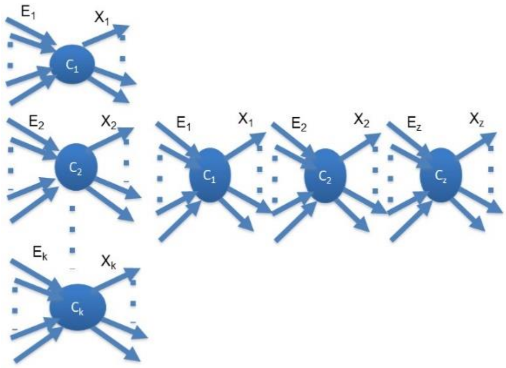

Fig 5: Toll Plaza Area and Sequence of Traffic Units

As an illustration (refer to Fig.5), assume that there are k equivalent toll booths arranged in parallel $(C_1, C_2, ... C_k)$. Then we have:

- Each C_i $(i = 1,2,..k)$ serves a vehicle in time t, and by its very nature k vehicles can be served within the same time t.
- The number of entry and exit lanes $|E_i|$ and $|X_i|$ $(i = 1,2,..k)$ do not contribute as explained earlier.
- There will be a build up at the queueing area if $n \geq k$ within the time t.

When n cars arrive within the time t at the queueing area, the cars may choose any of the k toll booths . Next we can assume they will distribute evenly. For example, if 6 cars arrive at 3 toll booths, they will disburse at 2+2+2, if 7 cars it would be 2+2+3, with 8 cars it would be 2+3+3, and so on. Fundamentally, the clearance time for this example at a particular toll booth is $2 * t$ for the first case and $3 * t$ for the next two cases.

With the example above, the clearance time T from Eq. (1) at a toll plaza area for n cars arriving at k toll booths is (here ⌈ symbols mean that 'rounding up to an integer value'):

$$T = \lceil n/k \lceil * t \qquad (1)$$

Eq. (2) is referring to a junction which is not a toll plaza area, but basically a merging area with a larger number of lanes group into a smaller number of lanes. The case is simpler to be compared with a toll plaza area. There is no servicing on C (no payment) which is then the same as having an equal number of 'booths' as there are exit lanes – in the case above $k = |E|$. The clearance time J for n cars arriving at junction is thus:

$$J = \lceil n/|E| \lceil * t \qquad (2)$$

If a junction or a toll plaza introduces a sequence of z bottlenecks (right hand side of Fig.5), the total clearance time for n cars arriving at the sequence would be:

- the aggregated sum of each clearance time for all toll plaza areas in the sequence,
- the aggregated sum of each clearance time for all junctions in the sequence,
- the aggregated sum of the time taken to move from one bottleneck to another in the sequence (there are $z - 1$ intervals).

We note the following: (1) The total clearance time is for the n cars arriving at C_1within the time t_1(the first unit in the sequence). As such, the value for n is the same for each $C_i(1 \leq i \leq z)$. (2) Each of the C_i will probably have a different t_i. (3) Each $C_i(1 \leq i \leq z)$ that is a toll plaza area will probably have a different k_i(the number of toll booths involved). (4) Each $C_i(1 \leq i \leq z)$ that is a junction will probably have a different $|X_i|$(the number of exit lanes).

When there are possible changes in the values of $k, |E|, t$ and n in Eq.(1) and (2), the overall achievement of the sequence are:

- From Eq. (1), the clearance time will reduce with an increase in the number of toll booths k (T decreases when k as the denominator increases).
- However, this improvement may be lower if the number of exit lanes $|E|$ in the junction shortly after is small, based on Eq.(2) (J increases when $|E|$ as the denominator reduces).
- In our discussion earlier, a junction may aggravate the situation if it is situated closely after a toll plaza. For example, a set of traffic lights, where a longer time t takes to clear its C. Another situation is for a point where more lanes from elsewhere join the current lane and thus contributing to an increase in the number of cars n.

4.0 IMPLEMENTATION

As a proof of concept and towards validation, we conducted an analysis on a realtime data set and a simulated data set. The realtime data set was adopted from the New York State Thruway (NYS Thruway Origins and Destinations Points) [29]. Their mode of payment by E-ZPass is equivalent to Smart Tag, and the Cash mode is equivalent to TouchNGo. Simulation was conducted using the S-Plus software to determine the average waiting time for the BTU model, and part of the program is as shown in Fig.6 . There were 20 sets of simulation run for this study. The average waiting time was simulated for both types of toll payment.

```
simubtu=function(n,m,miu1,miu2,sig1,sig2,alpa,simu)
{
   maxBTUEZ=matrix(0,nrow=simu)
   maxBTUCS=matrix(0,nrow=simu)

   minBTUEZ=matrix(0,nrow=simu)
   minBTUCS=matrix(0,nrow=simu)

   meanBTUEZ=matrix(0,nrow=simu)
   meanBTUCS=matrix(0,nrow=simu)

   for(i in 1:simu)
   {
         maxBTUEZ[i]=btu(n,m,miu1,miu2,sig1,sig2,alpa)$maxbtuez
         maxBTUCS[i]=btu(n,m,miu1,miu2,sig1,sig2,alpa)$maxbtucs

         minBTUEZ[i]=btu(n,m,miu1,miu2,sig1,sig2,alpa)$minbtuez
         minBTUCS[i]=btu(n,m,miu1,miu2,sig1,sig2,alpa)$minbtucs

         meanBTUEZ=(maxBTUEZ+minBTUEZ)/2
         meanBTUCS=(maxBTUCS+minBTUEZ)/2
   }
   meanbtuez=sum(meanBTUEZ[,1],na.rm=TRUE)/simu
   meanbtucs=sum(meanBTUCS[,1],na.rm=TRUE)/simu
   #BTUEZ=BTUEZ,,BTUCS=BTUCS

   list(meanbtuez=meanbtuez,meanbtucs=meanbtucs)
}
```

Fig 6: Simulation with S-Plus for BTU

The data were simulated for 23 hours. Various bodies such as policy-makers, researchers, and transportation experts have worked on developing different measurement approaches to estimate traffic congestion accurately [30]. [31], [32] concluded that there is currently no concensus on a fixed universal method to measure traffic conditions. In different countries, even for different states in a single country, one would measure congestion differently. [30] compared each measure in a small-scale case study, where various traffic congestion measures were studied. There are indeed many ways to define congestion. Congestion is defined by an increase in road users' traveling time due to some disruption of normal traffic flow. Congestion is also defined as the time the road users must tolerate a jam caused by the increasing number of vehicles. In this paper, congestion is interpreted as waiting in a system for a certain amount of time. A system consists of a queueing area and a service area. Since congestion is associated with a longer waiting time, we computed the mean waiting time. In a large city, waiting for more than 10 minutes is considered unbearable, but in the countryside, it is probably tolerable. In this paper, congestion is regarded as waiting for more than 10 minutes or equal to 600 seconds. The figures are our conjecture based on local conditions. From the definition in Queueing Theory, the waiting time in the system is equivalent to the time waited in line and the duration of being served. For the toll plaza case, the waiting time in the system for the cars is when the cars are in the queue waiting to pay the toll plus the duration of time the cars pay the toll (in-service) at the toll booth.

5.0 RESULTS AND DISCUSSION

From the realtime data set, we calculated the total service time and the total average service time for the two modes of payment. We also calculated using the formulae developed from the BTU for the same two modes of payment using this realtime data set. Another set of data for the arrival number of vehicles was simulated using the S-Plus software. Using this simulated data, we calculated the total average service time using the formulae developed from the BTU for the two modes of payment.

To ensure that the value of the total mean service time from the realtime data set and the total mean service time from the simulated data set were not much different, we computed a 95% confidence interval for the two modes of payment for the purpose of comparing. The results from the realtime data set computed using BTU's formulae as well as the results from the simulated data set computed using BTU's formulae were found to be within the 95% confidence interval. This indicates that the BTU is able to calculate the value of the total mean service time almost the same as either from the realtime data set or from the simulated data set. Since we set the value for congestion is at 600sec, we can see that from the data set (red boxes in columns 5 & 7) that the TouchNGo mode of payment shows the congestion is building up. This demonstrates that BTU can calculate and predict congestions based on the calculated values shown in Table 1.

From Table 1, the green boxes represent the 95% confidence interval for the total average service time for TouchNGo. If we compare the values from the red boxes (in columns 5 & 7) and from the green boxes (last column), we can see that the values in the red boxes are within the values in the green boxes. The same thing can be seen for the Smart Tag columns of the realtime data set and the simulated data set.

Table 1: The Analysis of the Real Data Set and the Simulated Data Set

Time	# of Vehicles per hour (REAL DATA)	total service time (sec)	total ave. service time (sec)		BTU Smart Tag (sec)	BTU TouchNGo (sec)	# of Vehicles per hour (SIMULATION)	BTU simulation using S+ (sec)		Mean BTU C.I (Smart Tag)		Mean BTU C.I (TouchNGo)	
			Smart Tag	TouchNGo				Smart Tag	TouchNGo	lower	upper	lower	upper
12:00 PM	223	112	96	283.5	208	395	220	201	385	36	392	119	591
1:00 PM	149	64	78	181.5	142	245	140	142	267	21	275	82	491
2:00 PM	82	31	51	94.5	82	125	80	92	186	6	166	41	246
3:00 PM	56	28	30	66	58	94	50	67	147	7	98	38	172
4:00 PM	51	31	27	60	58	91	50	20	67	15	90	23	153
5:00 PM	59	25	18	76.5	43	102	60	43	106	11	111	41	179
6:00 PM	117	70	39	153	109	223	110	99	215	26	203	54	302
7:00 PM	154	46	75	190.5	121	237	150	117	227	34	284	91	427
8:00 PM	152	65	72	189	137	254	150	124	249	35	282	90	424
9:00 PM	245	82	93	318	175	400	240	167	305	53	454	147	688
10:00 PM	287	108	111	372	219	480	280	187	339	64	529	148	777
11:00 PM	313	104	129	402	233	506	310	213	380	62	697	170	864
12:00 AM	362	121	144	468	265	589	360	235	415	84	402	214	968
1:00 AM	388	146	150	504	296	650	380	259	456	80	726	217	972
2:00 AM	390	130	192	486	322	616	390	285	456	76	731	207	975
3:00 AM	441	132	255	531	387	663	440	308	540	69	850	316	1041
4:00 AM	423	127	216	523.5	343	650	420	333	570	64	829	143	1018
5:00 AM	511	139	219	25.5	358	651	510	332	572	108	987	484	1657
6:00 AM	513	154	195	669	349	823	520	338	627	81	991	327	1488
7:00 AM	447	168	219	558	387	726	440	342	587	72	861	260	1050
8:00 AM	330	110	147	418.5	257	529	330	319	547	68	632	172	913
9:00 AM	288	96	111	373.5	207	470	280	292	504	60	535	167	799
10:00 AM	228	68	147	265.5	215	334	220	266	366	48	414	128	622
11:00 AM	164	62	90	198	152	260	160	173	324	37	299	88	445
12:00 PM	190	63	66	174	129	237	190	130	246	23	201	110	541
1:00 PM	140	42	30	127.5	72	170	140	116	219	30	267	91	410
2:00 PM	97	29	21	93	50	122	90	41	103	1	192	47	250
3:00 PM	71	4	27	105	31	109	70	34	78	12	131	40	202
4:00 PM	81	27	30	151.5	57	179	80	63	112	16	153	18	190
5:00 PM	113	38	72	360	110	398	110	102	202	29	206	39	285
6:00 PM	266	114	69	339	183	453	260	126	242	57	493	160	751
7:00 PM	251	69	117	405	186	474	250	196	362	33	498	163	731
8:00 PM	311	93	141	459	234	552	310	236	430	74	578	169	872
9:00 PM	355	89	84	562.5	173	651	350	220	545	71	675	240	1035
10:00 PM	378	103	153	543	256	646	370	229	622	56	729	226	1062
11:00 PM	415	125	156	535.5	281	660	420	281	545	89	802	246	1192
12:00 AM	411	137	174	514.5	311	652	410	301	605	85	777	193	1106
1:00 AM	403	110	168	576	278	686	400	203	579	79	772	222	1126
2:00 AM	442	147	234	578	381	725	440	380	749	92	835	243	1234
3:00 AM	462	107	201	631.5	308	738	460	303	697	92	489	244	1268
4:00 AM	490	147	237	615	384	762	490	328	733	97	946	261	1355
5:00 AM	491	147	246	565.5	393	713	490	253	670	111	924	245	1341
6:00 AM	461	173	0	471	173	644	460	170	657	94	887	257	1288
7:00 AM	374	187	150	417	337	604	370	329	654	74	715	203	1033
8:00 AM	330	141	147	439.5	288	581	330	306	538	55	646	164	901
9:00 AM	344	129	153	348	282	477	340	281	510	76	646	140	901
10:00 AM	285	122	102	343.5	224	466	280	249	478	59	298	141	769
11:00 AM	265	99	80	188	179	287	270	129	259	65	506	185	800

- Column 2 is the total number of vehicles recorded at the given time of the day.
- Column 3 is the total service time from the real data set.
- Column 4 is the total average service time for the real data set and separated into two modes of payment, which are Smart Tag and TouchNGo.
- Column 5, we calculated the average service time from the real data set using the formula developed in BTU for the two modes of payment.
- Column 6 is the total number of vehicles generated by simulation.
- Column 7 we calculated the total average service time using the formula developed in BTU for the simulated data set by S-Plus.
- Column 8, 9, 10 and 11, we calculated the 95% confidence interval for the two modes of payment.

Given this, it is confirmed that BTU is able to predict congestions.

6.0 CONCLUSION AND FUTURE WORK

This paper presented a new model called Basic Traffic Unit (BTU) to predict possible congestions at toll plazas. Two types of data sets, namely a realtime data set and a simulated data set, were used to demonstrate the calculations for the total mean service time using the BTU's formulae. The Resulst and Discussion section above validates the claim that BTU is useful for predicting congestions. Further work can be carried out on the theory and on the applications side of the BTU. The future work for applying BTU may include: (1) proposing immediate solutions to existing problems; (2) proposing long term solutions; (3) planning new traffic networks; and (4) designing new toll plaza areas. Some existing network flow algorithms may be combined and used with the BTU model, such as Dijkstra's algorithm, Maximum Cost Flow algorithm, Minimum Cost Flow algorithm, Out-of-Kilter, Travelling Salesman, and Chinese postman.

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