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Design of a Distributive Robotic Vehicle Controller for Nigeria Toll Gate

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ABSTRACT

Nigeria toll gate was established in 1978 with the objectives of generating income to the Federal Government for the maintenance of the roads and also create employment for Nigerians. However, the tolls were demolished by President Obasanjo's government on the first of January 2004 at a cost of about #200 to #400 million naira. Among the reasons given were the issue of corruption, traffic congestion and keeping vehicles waiting for long. In 2012, the Buhari led administration re-lunched the toll gates with similar objectives. While the issue of corruption is still on the high side, that of waiting time of vehicle is also a great challenge. This research addresses the waiting time issue by proposing a Distributive Robotic Vehicle Controller (DRVC) for Nigeria toll gate. This DRVC uses counter to count the incoming vehicles on each service lane to know the length of queue of the vehicles. If the length of the queue in any of the lanes reaches the given threshold, then control switches to the lane with smallest queue length. Two approaches were used to demonstrate the proof of concept of the designed system. The first is the mathematical model and the second is the prototype demonstration on the first, we use the Non Preemptive Queuing M/M/c queuing model and on the second a discrete event simulator known as Arena software is used. Evaluation of this work is carried out with the current un-controlled existing system based on waiting time and waiting costs. The result reveal that the proposed DRVC had a better and high waiting time gain difference compared to the un-controlled system Also, we recorded lower waiting costs compared to the conventional un-controlled system. However, at the peak, they almost have the same performance, this is attributed to the fact the threshold of all the lane are reached and more vehicles have to wait. This model is hope to play a significant role in traffic control in our various toll gate in Nigeria

Keywords: Robot, vehicle, arrival time, queue length, waiting time

1. INTRODUCTION

Toll gate is a gate on a road or bridges at which one pay an amount in order to be allowed to use the road. Nigeria toll gate was established in 1978 with the objectives of generating income to the Federal Government for the maintenance of the roads and also create employment for Nigerians.

This is not only for road alone but for other infrastructure projects that are finance directly by their users with the aim of keeping a country's other taxpayers from having to subsidize that road project. However, the tolls were demolished by President Obasanjo's government on the first of January 2004 at a cost of about #200 to #400 million naira. Among the reasons given were the issue of corruption, traffic congestion and keeping vehicles waiting for long. Some scholars condemn President Obasanjo for taking this step. For example, In[1], The author described the decision to abrogate toll plaza, as a disservice to road maintenance. In 2012, the Buhari led administration re-lunched the toll gates with similar objectives with the goal of generating over ₦365 billion yearly [2], [3]. While some of the issues raised for demolition of toll gates still persist, that of traffic congestions and keeping vehicles waiting for long is a big challenge.

Amongst the reasons attributed to this is the rapid growth of industries and infrastructure in Nigeria that has triggered the traffic density on the roads especially on the toll gates. This is because the arrival rate of vehicles has greatly increased the waiting time therefore leading to long queue of vehicles. One performance measure that determines the operational effectiveness of a toll plaza is the Queue length. This Queue length is directly proportional to the waiting time. That is, the longer the queue the longer is the waiting time of commuters in the toll gates. This waiting time results in losses in terms increased fuel costs, increased pollution, delay in delivery of goods and services and increase in opportunity cost in the form of wastage of valuable time of commuters which as a consequence will lead to frustrations to the commuters[4][5].

That means that average travelers on the road believe in time reliability (TR) and no one wants any delay especially on our toll gates. This is because unexpected delays have marginal economic consequences on the passengers and the drivers in our toll gates. That means the utility maximization of Nigeria toll is important [6] [7]. On the commuters' side, the amount generated is based on the number of trips they can make per day. Any delay experienced on the road especially at the toll gates will have effect on their income. In order to balance this, some drivers increase their speed and this sometimes lead to accident on Nigerian roads[8]. Despite the fact that the International Monetary Fund (IMF) ranked Nigeria 143 out of 162 countries with low-speed roads and among countries with the lowest speed range of 30-60 km/hr, Nigeria government loses about 80 billion naira annually to road accidents. Out of this, 29.1 per cent suffer disability and 13.5 per cent are unable to return to work[9] . In addition, a total of 4,283 road crashes were recorded across the country in Q1 of 2022. More than half (59.79%) of such crashes were caused by speed limit violations[10].

To tackle this delay on our toll gates, this work is into designing a Distributive Robotic Vehicle Controller (DRVC) that will reduce time delay in Nigeria Toll Gate. Two approaches are used to demonstrate the proof of concept of this system. The first is the mathematical model using queuing theory and the second is the prototype demonstration. On the first, we use the Non Preemptive Queuing M/M/c queuing model and on the second a discrete event simulator known as Arena software is used. Our justification for using the queuing theory is that this theory is based on analysis of delay. It mainly focuses on the delay when demand exceeds its capacity. Such delay is known as queuing delay. The main goal is to minimize the waiting time of a particular queueing system.[11]. It is based on the fundamental concept of some terms like servers, streams of customers demanding for services, queue length and others. In our concept, the toll collectors serve as servers, the vehicles with commuters serve as the customers.

The organization of this paper is as follow. Chapter two discusses about the literature review. In chapter three, the design of the distributive Robotic Vehicle Controller is discussed. The results and discussion section is in chapter four and the paper ends with conclusion in chapter five.

2. LITERATURE REVIEW

Many scholars have proposed the use of queueing theory to address various problems. For example, the works of [12][13][14] used the queueing theory in the context of cloud computing. Some authors, approaches the issue of road congestion problems using the queueing theory. For example, in[15], the author studied the traffic flow on toll gates using queueing theory. The author submitted that the increase in traffic congestion is due to increasing vehicles on the road which produces many problems. Analysis of Queue at a Nigerian Toll Plaza was modelled in [16]. The work is based on knowing effectiveness measures which provide indices that contribute to the unsatisfactory toll booth service at the Kaduna – Zaria Road in Nigeria. The work in [17] uses the M/M/c queueing theory for the Optimization of Toll Plaza in India.

The study designs and evaluates the model in Asbury Park Toll Plaza based on cellular automata and M/M/C queuing theory. Three parameters were used. These are: safety coefficient, throughput and cost. The result shows that the optimized M/M/C queuing model proved to be safer and preferable. In [18] , the authors presented their work based on the usage of multi-server queuing model. The performance analysis based on the optimal number of toll booths to reduce the queue length and waiting time of vehicles at toll plaza. In [19], the authors further solved the waiting time problem by using Linear programming approach with python language. This is done by the translating the total expected cost of the multi-server queuing model into linear programing problem subject to the constraints and solved the linear programing problem with Python program language.

The use of mathematical model and a simulation model using the CPN tools to investigate the queuing parameters in Addis-Adama expressway toll service in Ethiopia was carried out in [20]. This is aimed at getting the optimum output by using economic analysis and identifying the minimum waiting time and operating cost without expense. The result shows that the performance of the toll service is a function of the number of servers, the number of vehicles in the system and queue, waiting time in the queue, service time, and inter-arrival time. The Use of Queuing Theory in the Management of traffic Intensity was carried out in [15].

The author adopted queuing theory to describe traffic intensity to get the performance measures. This is then us in the prediction of the level of queue build-up at traffic light intersection in the selected areas In Lagos State, Nigeria. This is to enhance proper traffic management that is devoid of undue delays. The use of multiple server queuing modeling system (M/M/S): (/FCFS) to monitor the traffic intensity was carried out in [21] . This was used to obtain the average waiting time of vehicles in the system and in the queue. The finding shows that traffic situation is intense on Mondays, Saturdays and Sundays.

Our work is similar to that of [17][18] [22][23] in the concept of applying queueing model as one our proof of concept. However, our work is distinct from these authors based on the followings:

i. Our work is in the area of Artificial Intelligence (AI) based on design of robotic vehicular system and the works of these authors are in the context of cloud computing.
ii. Most of these works are on cloud optimisation based on cost and consumers' waiting time while ours is on reducing the queue length on Nigeria Toll gates. Those works on toll gates using queueing theory are into obtaining the performance measures with the aim of suggesting to commuters when the traffic will be heavy.
iii. Our work uses the performance measure to signal the developed DRVC to direct the vehicle from entering a long queue thereby reducing waiting time.

3. PROPOSED DISTRIBUTIVE ROBOTIC VEHICLE CONTROLLER (DRVC)

The Proposed DRVC consists of three service counters that are networked together. The collection of tolls takes place at these service counters. The model is represented by the diagram in Figure 1. Each counter has two lights (Red and Yellow) mounted on top facing the direction of the incoming vehicles. An Arduino Nano robotic controller is mounted on each counter. The operation is such that when vehicles are coming, the yellow light is on and each controller starts counting the incoming vehicle. As soon as it reaches the threshold say k, the light switches from yellow to red and alarm buzzer will sound indicating that "the Queue is full".

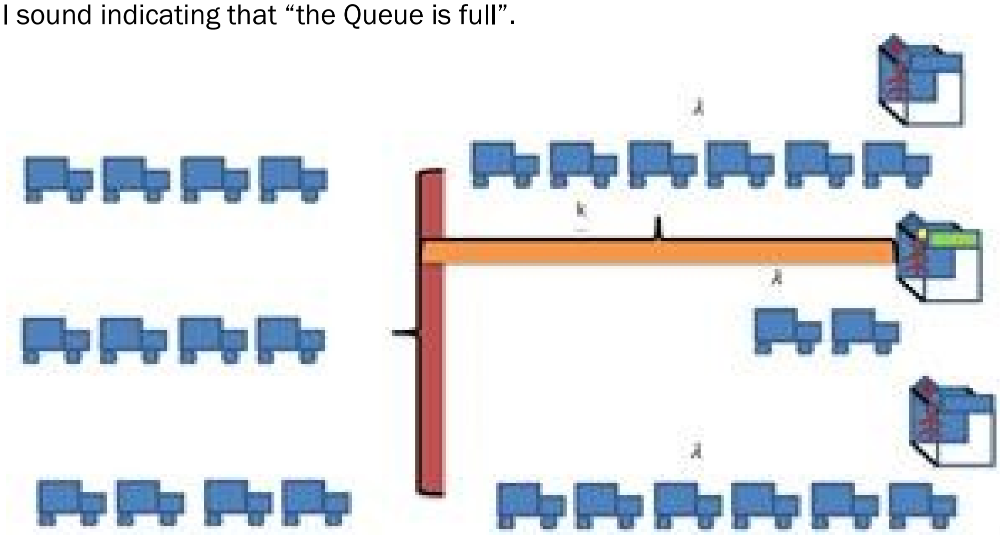

Figure 1: Robotic Control Model

This will allow the incoming vehicle to move to other counter with less that N number of vehicles. As soon as k reduces by y, then the yellow light is back again. When all the counters have N number of vehicle, then no vehicle will be allowed until the queue length reduces to k=y. Two modelling techniques are proposed: the first is the queueing model and the second is by applying simulation using Arena 15.10. Under the two models, it is assumed that the arrival and the service rate of the incoming vehicles follow a Poisson process.

The focus of this work is to determine the conflicting measures of performance. For example, the average queue length and the average waiting time. This is achieved by applying the six steps stated in [24] and the law of conservation of flow in [25].

3.1 Modelling The Queue Counter Stations As M/M/c/k

The counter station is the one providing the issuance of ticket service based on Non-Priority First Come First Served (NPFCFS). Each queue counter is modeled as M/M/c/k with equal service distribution $k_i\lambda$ where k is the maximum number of vehicles allowed on the queue and c is the number of service counter(s). where i= 1,2,3,....j represents the number of queue counters and one of the assumption is that, each service counter(c_i) has equal or identical counter collectors with the same service rate μ. For example, queue counters 1 that has arrival rate $k_i\lambda$ has a service rate μ. Therefore, for each queue counter station, the mean arrival rate is given by

$$k_i\lambda_{\mathrm{eff}_n} = \begin{cases} k_i\lambda & \text{for } n = 0, 1, 2 \ldots . N-1 \\ 0 & \text{for } n = N, N+1, \ldots \ldots \end{cases} \qquad (1)$$

and

$$\mu_n = \begin{cases} n\mu & \text{for } n = 0, 1, 2 \ldots . c-1 \\ \mu & \text{for } n = c, c+1, \ldots \ldots \end{cases} \qquad (2)$$

where $1 < c < N$

Given the steady- state probabilities P_n and P_0, then

$$P_n = \frac{k_i\lambda_0 \, k_i\lambda_1 \ldots \ldots \ldots \ldots . \, k_i\lambda_{n-1}}{\mu_1 \mu_2, \ldots \ldots \ldots . \ldots ., \mu_n} P_0 \qquad (3)$$

$$P_0^{-1} = 1 + \sum_{n=1}^{\infty} \frac{k_i\lambda_0 \, k_i\lambda_1 \ldots \ldots \, k_i\lambda_{n-1}}{\mu_1 \mu_2, \ldots \ldots, \mu_n} \qquad (4)$$

substituting the value $k_i\lambda_d$ and μ_n

$$P_0 = \left[\sum_{n=0}^{c-1} \frac{1}{n!}\left(\frac{k_i\lambda}{\mu}\right)^n + \frac{1}{c!}\left(\frac{k_i\lambda}{\mu}\right)^c \sum_{n=c}^{k}\left(\frac{k_i\lambda}{\mu}\right)^{n-c}\right]^{-1} \qquad (5)$$

and

$$P_n = \begin{cases} \frac{1}{n!}\left(\frac{k_i\lambda}{\mu}\right)^n P_0 & \text{for } n \le c \\ \frac{1}{c!c^{n-c}}\left(\frac{k_i\lambda}{\mu}\right)^n P_0 & \text{for } c < n \le k \\ 0 & \text{for } n \le k \end{cases} \qquad (6)$$

Therefore the expected number of vehicles in the queue of each queue counter station i is given by

$$E\left(counter\ queue_{i_i}\right) = \sum_{n-c}^{N} n - c \frac{1}{c!c^{n-c}}\left(\frac{k_i\lambda}{\mu}\right)^n P_0 \qquad (7)$$

but the server utilisation in each counter station i is $\rho_i = \frac{k_i\lambda}{c\mu_1}$. Substituting $\rho_i$in Eq. 5 and differentiating $\frac{d}{d\rho_i}\left[\frac{1-\rho_i{}^{N-c+1}}{1-\rho_i}\right]$ **then**

$$E\,(counter\ queue_i) = P_0 \frac{k_i\lambda_d}{\mu} \frac{\rho_i}{c!(1-\rho_i)^2}[1-\rho_i{}^{N-c} - (N-c)(1-\rho_i)\rho_i{}^{N-c}] \qquad (8)$$

The expected number of vehicles in the system is given as

$$E\,(\text{counter system}_i) = \sum_{n=0}^{c-1} nP_n + \sum_{n=c}^{N} nP_n \qquad (9)$$

Therefore, the modified Little's formula then becomes

$$E\,(counter\ system_i) = E\,(counter\ queue_i) + \frac{k_i\lambda_{eff}}{\mu} \qquad (10)$$

Where $k_i\lambda_{eff}$ is the real effective arrival rate given as

$$k_i\lambda_{eff} = \mu\left[c - \sum_{n=0}^{c-1}(c-n)P_n\right]$$

The counter system and queue waiting time are:

$$\text{Wsystem}_i = \lfloor k_i\lambda_{eff} \rfloor^{-1} * E(\text{counter system}_i) \qquad (11)$$

$$\text{Wqueue}_i = \lfloor k_i\lambda_{eff} \rfloor^{-1} * E\,(\text{counter queue}_i) \qquad (12)$$

The average mean waiting time in the queue and system of all the counter queue and counter stations are given as

$$\text{Wqueue}_{ave} = \frac{1}{j}\sum_{i=0}^{j} \text{Wqueu}_i \qquad (13)$$

$$\text{Wsystem}_{ave} = \frac{1}{j}\sum_{i=0}^{j} \text{Wsystem}_i \qquad (14)$$

This queue length of queue in the system ($E\,(\text{counter system}_i)$) which is for each counter station is now used by each of the robotic controller to determine when the yellow or red light that will be on. For example, if the maximum vehicles allowed on the queue$_1$ (k) is 10 and $\text{Wsystem}_i = 10$ then the red light is on otherwise the yellow light is shown. The red light will be on until k reduces by certain number "y" before it can be switched back to yellow. That implies the threshold (t) is y+2. The algorithm is depicted in Table 1. The Average waiting time on the queue and in the system are then recorded and evaluated with the uncontrollable system.

Table 1: Robotic Controller Algorithm

```
j_i ← E (web system_i)_i
Count ← o
time← x
t ← y+2
5  Do
     If (j_i < 10) or ((j_i >t)
         Light ← "yellow"
     Else
         Light ← "Red"
         Threshold ← k-y
   Until sett =time
   End
```

3.2 Simulation

Arena v15.10, which is one of the most widely-used and comprehensive discrete event simulation software in the world, is used. A total of five queue counter stations were used. the inter arrival time is set to .33 seconds, and the service time for each of the counter queue counter station is set to 1.2 seconds with buffer capacity of 1000 with allocation $5 to cost of waiting. The base time unit is set to minutes. Each experiment is conducted with 10 replications for an average of 49949,0000 seconds. At the end of each experiment, the arrival rate is increased to calculate the gain or loss in the average waiting time in the queue and the system. That is, $\lambda = .2,\ .3, .4, .5, and\ .6, .7$ respectively in each of the service counters and μ (service time) to a constant value. These performance measures were then evaluated with the un-controllable or direct toll gate system.

3.3 Numerical Validation And Simulation

In order to ascertain the degree of correctness, we first validate our mathematical solution with the simulation. We achieved this by setting the simulation and the analytical parameter to the same value. That is, $\lambda = .2,\ .3, .4, .5, and\ .6$ respectively in each of the service counters and μ (service time) to a constant value. Wolfram Mathematical 9.0 is used as the mathematical tool for the validation of our mathematical results. This simulation was run with replication length of 1000 in 24 hours per day with base time in hours and replicated 5 times. The service rate was set to 0.0005 for each of the queue counter stations. The results and the explanation are given under the results and discussion section in chapter four of this work.

4. RESULTS AND DISCUSSION

The result of our mathematical solution with the simulation is shown in Figure 2 and Table 2. The average Total Waiting time of vehicles recorded in various counting lanes under analytical approach is almost the same with our simulation. That validates our proof of concept.

Table 2: Analytical and simulation waiting time

	ANALYTICAL Time			Total		SIMULATION Time		Total
λ	Counter 1	Counter 2	Counter 3	Waiting Time	Counter 1	Counter 2	Counter 3	Waiting Time
0.2	2.05	2.02	2.04	6.11	2.05	2.03	2.03	6.11
0.3	3.17	3.07	3.09	9.33	3.17	3.17	3.09	9.43
0.4	3.92	3.89	3.86	11.67	3.92	3.92	3.86	11.7
0.5	4.32	4.42	4.28	13.02	4.32	4.43	4.29	13.04
0.6	4.85	4.75	4.9	14.5	4.85	4.75	4.89	14.49
0.7	5.52	5.49	5.57	16.58	5.52	5.5	5.57	16.59

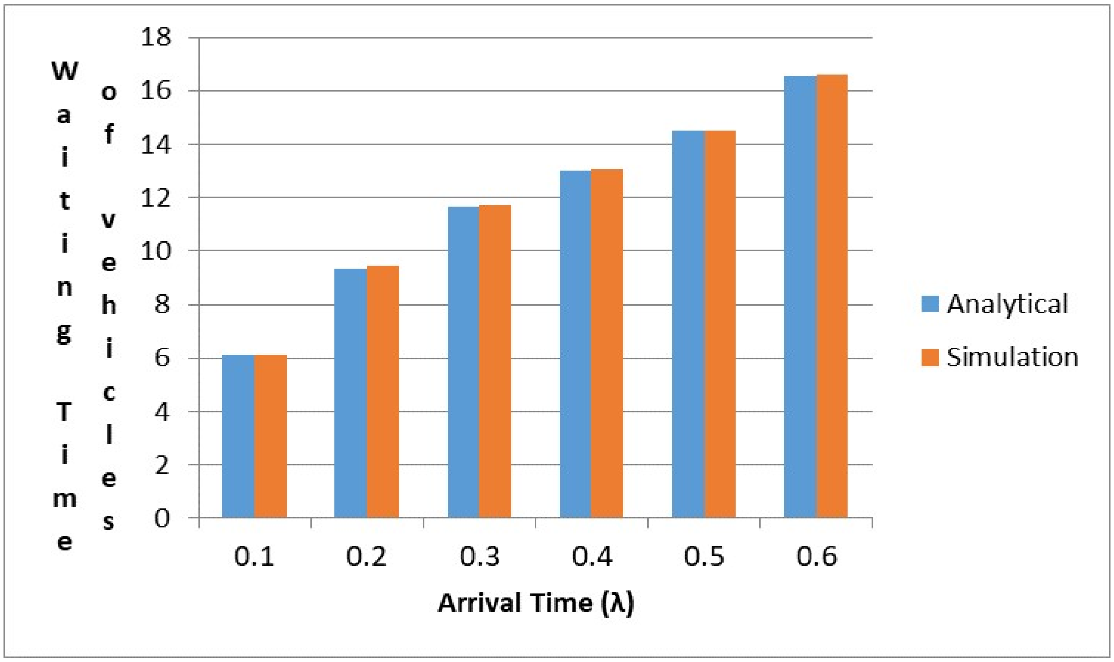

Figure 1: Analytical and Waiting Time Proof of Concept

The result of our robotic control system and the un-controlled one is depicted in Figure 3. In this result, it is observed that, as the arrival rate of vehicles increases, the waiting time increases. However, the waiting time difference is well noticeable between the DRVC and the Un-controlled system especially when λ=0.1, 0.2, 0.3. For example, when λ= 0.1, the waiting time difference is about 2.18hrs. Also, when λ= 0.2, the difference is 3.24.

The gain difference is depicted in Figure 4. From this Figure 4, it is observed that the waiting time gain difference increase to a certain point and later decrease. This is attributed to the fact that at the initial arrival of vehicles to toll gate, the queue length is not much so robotic control system can easily switch to less busy counter provided the threshold is not reached. However, as the arrival rate of vehicles increases, the threshold of the all the lane are reached quickly and more vehicles have to wait, This accounted for the reduction in the gain experienced.at this peek point, the toll counter needs to be increased to reduce the waiting time.

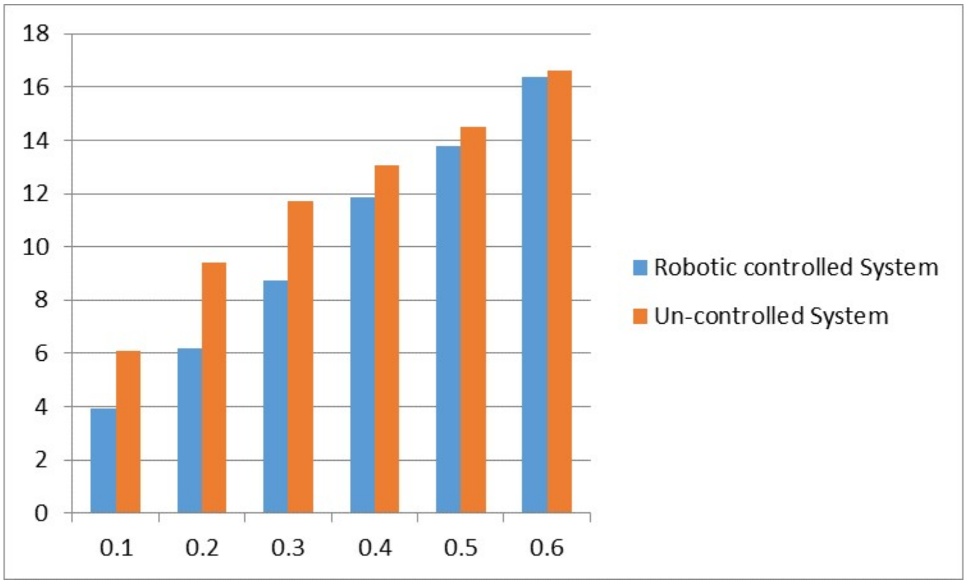

Figure 2: Robotic Control System and the Un-controlled System

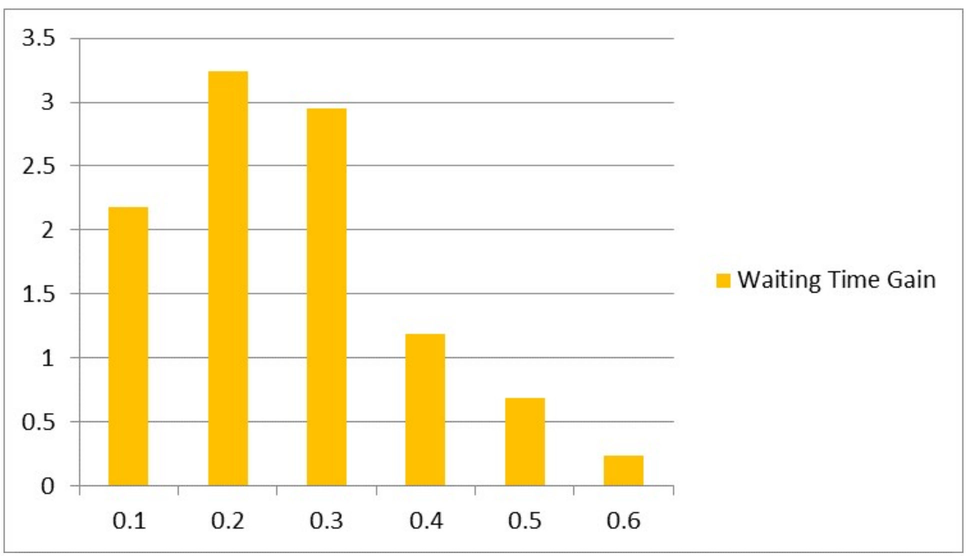

Figure 3: Waiting time gain

We further evaluate this work based on cost of waiting between our DRVC and the un-controlled system. This is done by considering the total expected cost using the concept in [23] .

This is given as:
Total expected cost = Total expected service costs + Total expected waiting costs
Total expected service costs = Number of Toll counter * Cost per Toll counter $=mC_s$
Where m = number of service toll counter and c is the cost per counter.

The waiting cost is given as

$(\lambda W_q)C_q$. .... (15)

where λ= arrival rate, W_q= waiting time and C_q is the waiting cost in q toll counter.

In this work, we assume that the Total expected service costs are the same for both our robotic system and the un-controlled system. In addition our waiting cost is based on the following:

Fuel, Pollution, Good delivery and Valuable time lost. Therefore, the total waiting cost is given as
$\sum_i^n (\lambda W_q C_q)_i$. .... (16)

The assumed associated costs are in Table 3.

Table 3: Associated waiting cost

	Fuel (#)	Pollution (#)	Good delivery(#)	Valuable time lost(#)
Cost	3500	4600	4000	4670

We used the Total waiting cost in equation 16 to get our Total waiting cost of our DRVC and the uncontrolled system. The result reveals that the DRVC had a lower waiting cost compared to the conventional un-controlled system as depicted in Figure 5 and Table 4 respectively. The reason is because of the switching from one long queue lane when the threshold is reached to less busy lane by the robotic controlled system. However, the waiting cost is less noticeable as the arrival rate increases. At this point, additional counter will be of great help. For example, when λ=.2, .3,.4, the gain difference were 36558.6, 54334.8 and 49471.5.However, it start dropping from λ = 0.5 and 0.6.

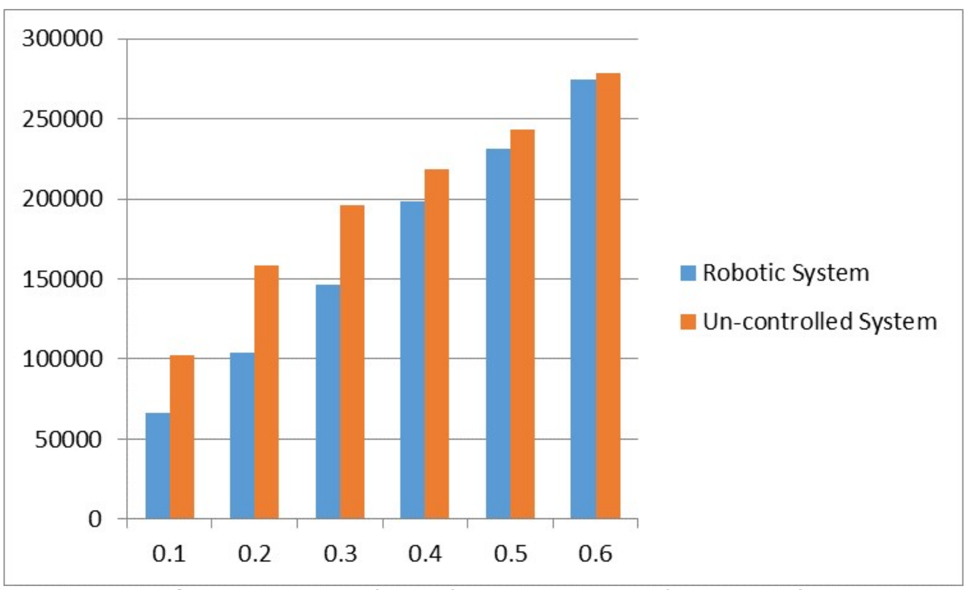

Figure 4: Total Waiting Cost of Robotic and Un-Controlled System

Table 4: Total waiting costs and difference

λ	Robotic	Un-Controlled	Gain difference
0.2	65906	102464.7	36558.6
0.3	103806	158141.1	54334.8
0.4	146738	196209	49471.5
0.5	198725	218680.8	19956.3
0.6	231426	242997.3	11571.3

5. CONCLUSION

Toll gate is a gate on a road or bridges at which one pays an amount in order to be allowed to use the road. The objectives of building toll gates all over the world including Nigeria are for: generating income to the Government, maintenance of roads and also create employment for Citizens. The Nigeria toll was established in 1978 and later demolished by the same Obasanjo government in 2004. Among the reasons given for the demolition were: corruption, traffic congestion and keeping vehicles waiting for long. The Buhari led administration re-lunched the toll gates with similar objectives in 2012. While some of the issues raised for demolition of toll gates still persist, that of traffic congestions and keeping vehicles waiting for long is yet to be fully addressed. This is because keeping vehicle waiting has great effect on commuters.

These include losses in terms increased fuel costs, increased pollution, delay in delivery of goods and services and increase in opportunity cost in the form of wastage of valuable time of commuters which will lead to frustrations to the commuters. To tackle this delay, this work designs a distributive Robotic Vehicle Controller (DRVC) to reduce time delay in Nigeria toll gates. Two approaches are used to demonstrate the proof of concept of this system. The first is the mathematical mode using queuing theory and the second is the prototype demonstration. On the first, we use the Non Preemptive Queuing M/M/c queuing model and on the second a discrete event simulator known as Arena software is used. Our results reveal that the arrival rate is directly proportional to the vehicle waiting time in both our DRVC and the conventional un- controlled system. However, the waiting time gain difference between our model and the un-controlled is higher, better and well noticeable when the arrival rate has not reached the peak. At the peak, they almost have the same performance, this is attributed to the fact the threshold of all the lane are reached quickly and more vehicles have to wait. Therefore, the toll counter needs to be increased to reduce the waiting time.

We further evaluate this work based on cost of waiting. This is done by considering the total expected cost. The result reveals that the DRVC had a lower waiting cost compared to the conventional un-controlled system. The reason is because of the switching from one long queue lane when the threshold is reached to less busy lane by the robotic controlled system. While this model is hope to play a significant role in traffic control in our various toll gate in Nigeria, further research can look into how the priorities model could be used on our toll gates especially for accident and other emergency cases.

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