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Traffic Flow Simulation and Development of Delay Models at Toll Plazas

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***Abstract*—The traffic in Metropolitan cities is very complex. Since in Indian traffic condition is heterogeneous, road safety is reduceded and congestion has become a major problem to vehicle users followed by increase in delays to vehicles. A toll road is a public or private roadway for which a charge is assessed for passage. It is a form of road pricing to help recoup the cost of road construction and maintenance, which amounts in the form of taxation.**

The present work is intended to highlight the general problems faced at toll roads. At toll plaza's the delays caused to the vehicle is prime concern since this delay causes loss of fuel and time. Two typical toll plazas around Hyderabad city were selected for the present study namely 1. Nanakramguda toll plaza which is located at outer ring road (manually operated) and 2. Choutuppal Toll plaza (RFID operated) along the NH – 09 (towards Vijayawada). As design criteria, these Toll plazas were designed in such a way that minimum time should be by the vehicle spent at these queuing areas. With this connection, analysis has been carried out at these selected toll plazas based on queuing theory which depends on certain parameters such as service rate, arrival rate, number of lanes and delays occurring. Regression analysis is conducted using multiple linear regression method and delay models are developed. These models are validated statistically. Further, the collected data is used for developing simulation models by using VISSIM software and the output obtained is compared with observed values. Chi- square hypothesis test is conducted for validation of the developed models with reference to VISSIM simulation results

***Keywords*—**queue length, Arrival rate, vehicle composition, speed and service rate.

I.INTRODUCTION

Toll tax is collected to recover the total capital outlay which includes the cost of construction, repairs, maintenance, expenses on toll operation and interest on the outlay. In India before the 4th century BC, the Arthashastra wrote the note on the use of tolls. Germanic tribes charged tolls to travelers across mountain passes. The new facility thus constructed should provide reduced travel time and increased level of service. Most of the highway projects in India are given on Public Private Partnership(PPP) mode. In this the private organization finance and constructs the facility and recovers the capital from the users in the form of toll tax. This tax is collected for a reasonable period of time after which the facility is surrendered to the public.

1.1 SCOPE AND OBJECTIVES

To evaluate the performance of selected manually operated and RFID operated toll plaza station along outer ring road and NH 63 based on a queuing theory.

1. To analysis the performance of a selected toll plaza station namely Nanakramguda toll plaza on outer ring road and Choutuppal Toll plaza on NH-9 based on multiple regression analysis.
2. To simulate the performance of a selected toll plaza station by using VISSIM software.
3. To suggest optimum no of toll booths required at toll plaza considering peak hours.
4. To compare the queue length and delays obtained by queuing theory and VISSIM software.
5. Comparison of service rate of RFID with manually operated toll plaza.

II.LITERATURE REVIEW

The following sections provide brief account of information of the available literature related queuing model of toll plaza and VISSIM microsimulation of toll plaza and of its applications with different case studies.

Zarrillo (1998) has developed a TP Model (Toll Plaza model), which is a analytical queuing model, for the purpose of estimating the peak hour delay at toll plazas. Uniform arrival rates were used to develop this model. It summarized the impact of ETC on traffic operations at toll collection facilities. A delay sensitivity analysis was also performed on each of the input variables like throughput, percentage of trucks, and percentage of ETC users of the model. This model estimates increasing delay with increasing approach volumes, increasing percentage of trucks utilizing the manual toll collection and estimates a decreasing delay with the increase in the percentage of ETC usage and increase in the service rate for the various services.

Hmad Hilmy and Abdul Hamid (2011)proposed congestion problems at the toll plaza as it becoming issue in a Malaysia.VISSIM a micro simulation is used to investigate various traffic operations and management configuration at several toll plaza locations in Malaysia. A simulation models of the selected toll plaza operations was developed. It was found that toll booths orientation, traffic volumes, types of toll service and storage capacity have influence on traffic operations and efficiency of the toll plaza.

The toll roads have become an alternative route choice for smooth, high speed and safe travel for daily commute between cities and within a city. As the number of road users opting for toll roads has increased and the toll gates become hot-spots for congestion and sometimes to intolerable conditions.

FengZhang (2017) has studied and found that the toll station, served as the bond to highways, has always been the bottleneck to the capacity of the highway. Based on queuing theory and probability distributions, the thesis builds the quantitative model of capacity and calculates two evaluation indicators to analyze the drawbacks of the traditional toll station.

The present study was conducted to observe the present scenario of traffic congestion at a highway toll plaza and how can we use Queuing Theory and draw the solutions to increase the efficiency in order to reduce the Queue length that is waiting time of the customers and their money in the form of fuel. There are multiple phases in which this study is carried to identification of the problem, collection of the data, data analysis and then toll plazas in Hyderabad was selected to do the analysis. The current operational effectiveness of can be drawn using data analysis and the parameters such as the Service Rates, Arrival Rates and the Number of toll booths.

III.METHODOLOGY

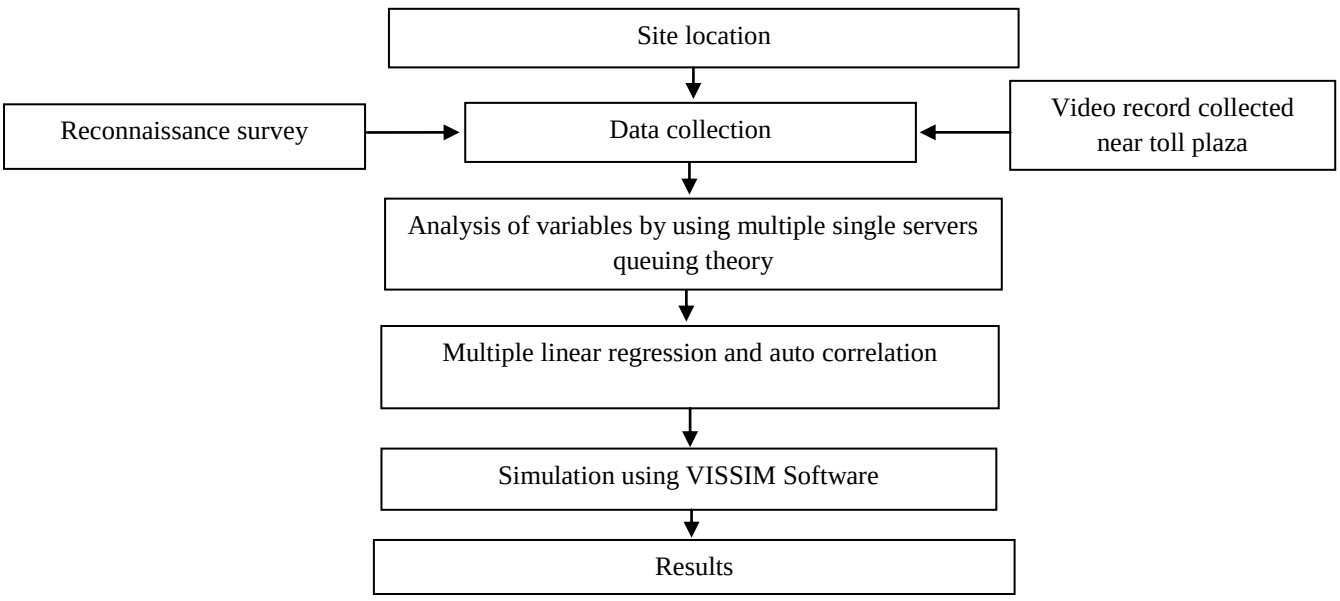

Fig. 1 Flow chart for Methodology adopted

3.1 STUDY AREA

Outer Ring Road Project (ORRP) for a length of 158km is taken up as a major infrastructure facility for the Hyderabad city by HMDA. The Project is planned as an 8-lane Access Controlled Expressway with a design speed on 120 Kmph. There are 19 interchanges at entry and exit junctions. The survey is proposed to be conducted Manual at Nanakramguda toll plaza which is 19th interchange of ORR and another toll plaza is Choutuppal Highway toll plaza.

Fig. 2 Satellite image of Nanakramguda toll plaza study area

Fig. 3 Satellite image of Choutuppal toll plaza study area

IV.DATA COLLECTION AND ANALYSIS

4.1 Data collection

The survey is proposed to be conducted at Nanakramguda toll plaza. The date of survey at interchange is on 5-1-18 during peak hours 9am to 11 am.

Table: 01 Traffic volume studies observed at Nanakramguda toll plaza (sample Data)

Date of survey	Time interval	Cars/ Jeep/Van/LMV	LCV/Mini bus	Bus /2-axle truck	Total volume	PCU
5-jan-18	09:00 to 9:15	270	15	6	291	311
	09:15 to 9:30	287	17	11	315	346
	09:30 to 9:45	325	11	4	340	354
	09:45 to 10:00	326	17	5	348	367

Table: 02 Service rate observed at Nanakramguda toll plaza (sample data)

S.NO	In	Out	Transaction time(sec)
1.	7.1	19.1	12
2.	2.7	12.7	10
3.	5.1	7.4	2.3
4.	5.6	11	5.4
5.	5.1	13.1	8

The survey is proposed to be conducted at Choutuppal RFID toll plaza. The date of survey at interchange is on 5-1-18 during peak hours 11 am to 4 pm.

Table: 03 Traffic volumes studies at Choutuppal RFID toll plaza (sample data)

Date of survey	Time interval	Cars/ Jeep/Van/LMV	Bus /2-axle truck	3-axle truck/ HCM	Total volume	PCU
19-04 -18	11:00 to 12:00	29	34	23	86	200
	12:00 to 01:00	10	15	21	46	118
	01:00 to 02:00	11	20	13	44	110
	02:00 to 03:00	17	13	10	40	86
	03:00 to 04:00	18	21	14	53	123

Table: 04 Service rate observed at Choutuppal RFID Toll plaza (sample Data)

S.NO	Transactions time(sec)
1	3.98
2	4.08
3	6.05
4	3.34
5	4.05
6	8

4.2 Analysis of variables by using queuing theory Multiple single servers' model

Queuing theory is the mathematical study of waiting lines, or queues. A queuing model is constructed so that queue lengths and waiting time can be predicated.

Multiple single servers' model is adopted for modeling of toll plaza with arrival rate and service rate following exponential distribution. In this model identical independent parallel servers receive vehicles from same source but in different parallel queues.

4.3 Modeling toll plaza Nanakramguda by using multiple single servers during peak hours observed data (manual toll booth)

N= 6lanes (Manual Nanakramguda toll plaza)

λ per lane = 236 PCU/Hour

μ = 300 PCU/Hour μ = 12 sec

$\rho = \frac{\lambda}{\mu} = \frac{236}{300} = 0.78$

Average no. of vehicles in the system = $\frac{\rho}{1-\rho}$= 4 PCU

Average no. of vehicles in the queue =$\frac{\rho*\rho}{1-\rho}$ = 3 PCU

average waiting time in the system =$\frac{1}{\mu-\lambda}$ = 57 seconds

average waiting time in the queue = $\frac{\lambda}{\mu(\mu-\lambda)}$ = 44 seconds

Wasted time =1/(μ - ϕ/T) = 1/(277 –236) =1.47 sec

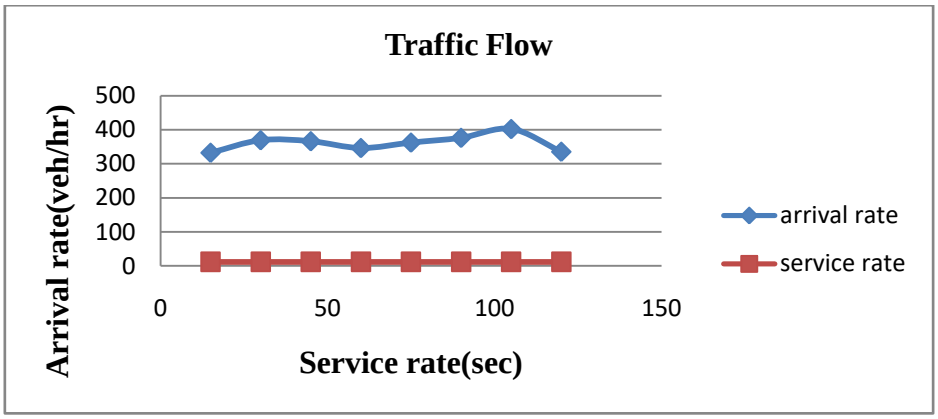

Fig. 4Varying arrival rate and constant service rate

4.4 Modeling toll plaza Choutuppal RFID by using multiple single servers during peak hours observed data (ETC toll booth)

N= 1lane (RFID at Choutuppal toll plaza)

λ per lane = 200 PCU/Hour

μ = 600 PCU/Hour μ = 6 sec

ρ = $\frac{\lambda}{\mu}$ = $\frac{200}{600}$= 0.33

Average no. of vehicles in the system = $\frac{\rho}{1-\rho}$ = 1 PCU

Average no. of vehicles in the queue = $\frac{\rho*\rho}{1-\rho}$ = 0 PCU

average waiting time in the system =$\frac{1}{\mu-\lambda}$ = 9 seconds

average waiting time in the queue = $\frac{\lambda}{\mu(\mu-\lambda)}$ = 3 seconds

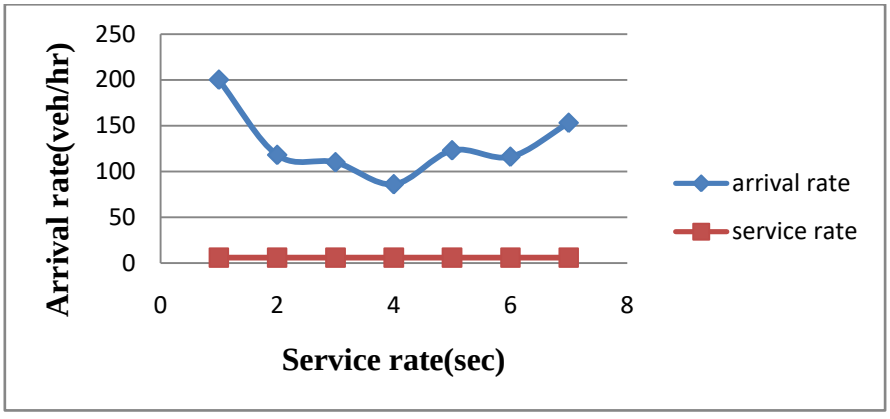

Fig. 5Varying arrival rate and constant service rate graph

4.5 Development of models by using multiple linear regression analysis

Multiple linear regression analysis is the statistical technique most often used to determine the optimum Number of toll plaza the aim of the analysis is to develop an equation in the following form to estimate the future optimum no. Of toll plaza from Nanakramguda toll plaza given the values for a set of arrival rate, service rate, speed and queue length.

$$Y = k + b_1X_1 + b_2X_2+b_3X_3+b_4X_4 +\ldots\ldots\ldots\ldots+ b_nX_n \quad \ldots\ldots.(Eq.01)$$

$$Y = 11.4586182 -0.030377628X_1+0.469391925X_2-0.04589316X_3-0.055722164X_4 \quad \ldots\ldots.(Eq.02)$$

R^2= 0.999845587 it's represented by strong relation between dependent and independent variable

Its best fit method

F= 1617.788> 4 it is acceptable

Therefore it's another alternative measure of the significance of the regression coefficient of each independent variable.

The Durbin-Watson Test is used for testing the hypothesis of independent and dependent variables of multiple linear regression analysis

$$\frac{\sum_{t=2}^{n}(e_t-e_{t-1})^2}{\sum_{t=1}^{n}e_t^2} \quad \ldots\ldots.(Eq.03)$$

$$d = \frac{0.0020}{0.00032}$$

$$d = 2.34$$

Its negative auto correlation

Sample size n = 6

K = 11.458

At 5% significance level

Based on n and k value taken d_l and d_u from D-W statistics 5% table

d_l= 0.610 and d_u = 1.400

2.34 >1.400

H_o accepted

Hence strong relation between independent and dependent variable of multiple linear regression analysis.

V. INTRODUCTION VISSIM

VISSIM is a microscopic, time step and behavior based simulation model developed to model urban traffic and public transit operations. The program can analyze traffic and transit operations under constraints such as lane configuration, traffic composition, traffic signals, transit stops, etc., thus making it a useful tool for the evaluation of various alternatives based on transportation engineering and planning measures of effectiveness.

Table: 06modeling toll plaza by using micro simulation given table

Input parameter	Output parameter
• Traffic volume • Service rate • Speed • Vehicle composition • Queue length • Travel time measurement	• Traffic volume • Delay • Queue length • Travel time measurement

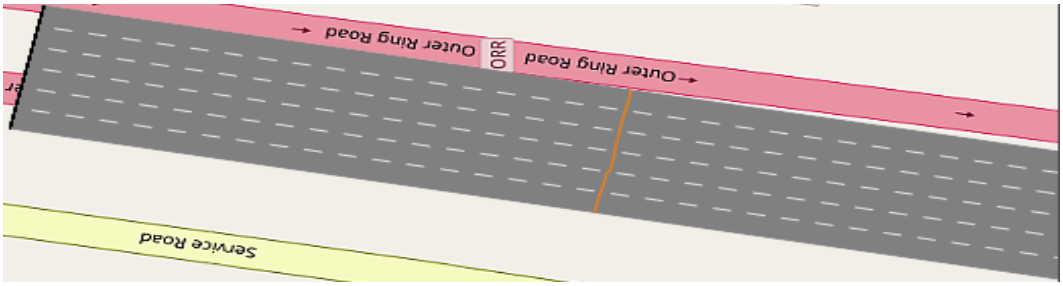

Fig. 6Toll plaza layout configured in VISSIM (left side only)

- orange lane represented by cash pay vehicles (Stop sign)

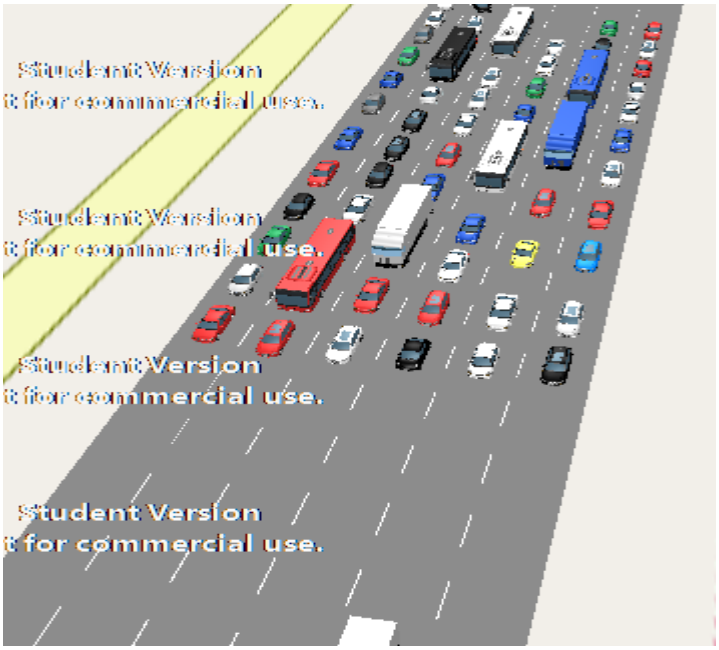

Fig. 73D Model of Toll operation using VISSIM

Table: 06 Queue lengths output from micro simulation

Simulation run	Time interval(sec)	Name	Queue length(m)	Max queue length (m)	Queue stops
1	0-3600	1: plaza	44.873	109.313	314

Table: 07 Travel Time Measurements output from micro simulation

Simulation run	Time interval (sec)	Vehicle travel time Measurement	Vehicle	Travel time (sec)	distance travel (m)
4	0-3600	1: toll plaza	42	47.084	113.19
5	0-3600	1: toll plaza	176	95.080	113.19
Average	0-3600	1: toll plaza	109	71.082	113.19
Standard deviation	0-3600	1: toll plaza	95	33.939	0
Minimum	0-3600	1: toll plaza	42	47.084	113.19
Maximum	0-3600	1: toll plaza	176	95.080	113.19

Table: 08 Delay output from Microsimulation

Simulation run	Interval time (sec)	Delay measurement	Stop delay (sec)	Stops	Vehicle delay(sec)	Vehicle	Person delay (sec)	Person
6	0-3600	1: toll plaza	46.36	4.926	74.497	176	74.495	176

Table: 09 Chi square variables

Variables	O_i	E_i
Arrival rate(veh/hr)	320	314
queue length(m)	110	109
Delay(sec)	1.47	0.43

Null Hypothesis H_o: Delay increase with arrival rate and queue length

Alternative Hypothesis H_1: Delay decrease with arrival rate and queue length

Degree of freedom = (r-1) (c-1) = (3-1) (2-1) = 2

Level of significance = 5%

Table value of chi square = 3.84

$\chi^2=\sum \frac{(O_i-E_i)^2}{E_i}$…. (Eq.04)

$$\chi^2 = 2.748$$

The calculated value of χ^2 is 2.748 is less than the table value 3.84 at 5% and df. Hence accept the null hypothesis and delay increase with arrival rate and queue length.

Suggested one exit booth based on queuing theory (M/M/N) at Nanakramguda toll plaza

M/M/N queuing system.

The arrival and service times of vehicles are assumed to be negative exponentially distributed. The system consists of multiple servers and is termed as multiple servers**.**

The probability of having no units in the system is $P_o = \frac{1}{\sum_{k=0}^{N-1}\frac{\rho^k}{k!}+\frac{\rho^N}{N!(1-\frac{\rho}{N})}}$ (05)

Average number of vehicles in the queue $L_q = \frac{\rho^{N+1}}{N!N} X \frac{P_o}{(1-\frac{\rho}{N})^2}$ (06)

Average waiting time of vehicles in the queue $W_q = \frac{L_q}{\lambda}$ (07)

Probability of having to wait in a queue $P_{k>N} = \frac{\rho^{N+1}}{N!N} X \frac{P_o}{(1-\frac{\rho}{N})}$ (08)

λ= 1414 veh/hr for 6 lanes = 24 veh/min

μ= 12sec = 5 veh/min

ρ= $\frac{24}{5}$ = 4.8

$\frac{\rho}{N} = \frac{4.8}{6}$ = 0.8 < 1

The value of time is 246Rs/hr

The wages and cost of operating plaza 2458Rs/h

S.No.	Name	For 6 booths	For 7booths
1	P_o probability of having no vehicle in the system	0.0104	0.0075
2	L average queue length	3.533veh	1.49veh
3	W average spent in the system	0.34min	0.262min
4	$P_{n>N}$ probability of having to wait a queue	0.706min	0.012min

Opening 7th plaza reduce the queue length is 3.533-1.49 = 2.043veh

Average time saved in the system = 0.34-0.262 = 0.08min

Since λ = 24 veh/ min

= 24veh/min X 0.08min =1.92veh/min

Total savings = 1.92veh/min X 60mins X246Rs

= 28339Rs/hr

Net savings = 28339-2458 = 25881Rs/hr

VI. CONCLUSIONS

6.1 General Conclusions

A detailed study was carried out to analyze the performance of selected Toll Plazas viz., manually operated at Nanakramguda toll plaza for observing exit six lanes toll plazas and RFID (ETC) operated at Choutuppal toll plaza for observing exit one lane toll plaza. The following observations were made:

- The traffic volume was found to be varying from 375 to 220 PCU/ hour on six lanes during peak hour at Nanakramguda toll plaza
- The inter arrival time between two vehicles was 12sec from observed data at Nanakramguda toll plaza
- The traffic volume was varying from 153 to 93 PCU/hour on only one lane of RFID during peak hour at Choutuppal toll plaza
- The inter arrival time between two vehicles was 6sec from Choutuppal toll plaza

6.2 Specific Conclusions

- Average waiting time in the queue was 44 sec and delay was 1.47sec obtained from queuing model Multiple Singer Servers (M/M/N).
- Average waiting time in the queue was 3sec obtained by using M/M/N model.

- The R^2 value obtained is 0.999 which indicates that there is a strong correlation between the independent and dependent variables. Thus the model developed is a best fit model.
- Number of toll booths increases with service rate as obtained from multiple linear regression analysis.
- A hypothesis test namely Durbin – Watson test was carried out and the obtained value was 2.34 which was a negative auto correlation according to theory. This represents a strong correlation relation between independent and dependent variables.
- Arrival rate was found to be 314 veh/hr, delay as 0.42sec and maximum queue length was 109.34m from simulation in VISSIM software
- The calculated value of χ^2 is 2.748 which is less than the table value 3.84 at 5%. Hence the null hypothesis that "delay increase with arrival rate and queue length" is accepted.
- Comparison of service rates for the two study areas (Nanakramguda toll plaza 12sec and NH 9 6Sec) shows that the service rates at Nanakramguda Toll plaza is more due to manual operation. This can be rectified by providing RFID technique or by providing separate lanes for cars.
- Suggested one exit booth at Nanakramguda toll plaza based on M/M/N model. Hence reduced average queue length was 2.043veh, average spent in the system was 0.08mints compared with 6 exit booth of average queue length was 3.533veh, average spent in the system was 0.34mints and Net saving cost was 25881rs/hour.

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