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Operational Optimization of Toll Plaza Queue Length Using Microscopic Simulation VISSIM Model

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Abstract

The toll plaza's efficient functioning can be depicted through the ease of selection of queue with minimum occupancy by the user and the smooth flow with the minimum waiting time. The arrival rate, toll booth's service features, and specific selection criteria of toll lanes by user influence the queue length and waiting time delays. The microscopic analysis is required to evaluate the driver's behavior to select the lane based on payment type and shortest waiting time in each lane. The paper focuses on the simulation of traffic at toll plaza through microscopic traffic simulation software VISSIM-2020. The output of the model is determined from the queue length, and the time delay is determined. The data collected from Delhi-Rohtak toll plaza for 1 month and all the payment types, including cash, Fast Tag, and exempted, are considered for the study. The study proposes a simulation model to determine the driver's pattern in selecting lanes and identifying the most appropriate lane and payment type for the toll plaza's minimum delay.

Keywords: Toll plaza, traffic simulation, VISSIM, queuing theory, traffic.

1. Introduction

Construction of long-distance roads like highways and road infrastructure improvisation act as the toll plaza's significant benefits. Multiple inclusive ranges of services like restaurants, banking services, gas stations, and motels at toll plazas implantation are transit points for financial benefits [1]. Apart from the advantage like minimizing average travel time, the heavy traffic load is a significant disadvantage, which further attracts the other adverse impact of heavy traffic like fuel wastage, environmental emissions, time wastage, a hindrance for emergency vehicles, etc. [2,3]. The issue of waiting times and queue length has been widely researched in various area such as healthcare [4], communication system [5] to resolve the issues related to long queues and network load handling. The lengthy vehicular queues and long delays hinder the functioning of the toll plaza. During heavy traffic, backup of vehicles in line to move for tollbooths, and scrambled position of the vehicle in lanes constitutes the major glitch in toll plazas' smooth functioning. Therefore, highway toll plazas necessitate distinctive explorations while consecrating their operations and subsequent collaborations with other roadway components [6,7].

Toll plazas are divided into three zones as merging area, queuing area, and toll booths. Increasing toll booths and managing queues in merging areas are considered critical resolutions to deal with heavy traffic congestion, the building of temporary queues in the queuing area [8]. Several factors increase the complexity of queue formation at the toll plazas during the peak hours, and its analysis requires microscopic simulation for the better understanding of all the factors that influence the queue formation [9,10,11,12,13,14]. The dependencies on the microscopic simulation for traffic analysis have increased recently as the simulation models are capable of analyzing the traffic pattern, type of vehicle, and queuing pattern. Simultaneously, these models can forecast the traffic for various payment types [15,16]. This study focuses on traffic flow simulation at the toll plaza to identify the most appropriate payment method using PTV VISSIM 8.0 simulation software [15,17].

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Different computer simulation and analytical models were designed for studying toll plaza configurations like toll collection methods, several toll booths, and type of vehicles [9,10,12,18]. Ceballos and Curtis [19] applied both the queuing and VISSIM for traffic simulation to determine the toll plaza traffic flow. Poon and Dia [20] applied the AIMSUN simulation model to analyze traffic at the toll plaza to determine the total revenue generated from the toll. The actual time at the toll for the tax collection was considered to determine the traffic flow and produce high accuracy. Klodzinski et al. [21] estimated the toll plaza traffic and considered different vehicle types to identify the drivers' lane selection behavior using the TPSIM simulation tool. Dubedi et al. [22] applied a microsimulation-based traffic simulation model to determine the toll booth's vehicle lane selection pattern. The input data were selected from the different toll booths to calibrate the model. The multiple software has been accepted worldwide with its vast application area. Velmurugan et al. [23] applied VISSIM to estimate the speed of the different types of vehicles on the multi-lane highway within their capacity and simulated the traffic flow with vehicles' maximum carrying capacity on the highway.

This paper employs a multi-server parallel multiple-queue queueing system for formulating the traffic flow at the toll plaza to identify the most appropriate payment method so that the minimum queue would get formed the toll. The simulation of flow at toll plaza under different combinations of arrival and service rate is carried out using PTV VISSIM 8.0, popular commercially available microscopic simulation software.

2. Study Area

The Delhi-Rohtak highway is situated on NH-9 before the town Sampla in Rohad village, as shown in Figure 1. The toll plaza operates on cash payment for single and multiple crossways within a day, and monthly passes are also available. The payment is also acceptable through cards, and recently Fast tag payment option has also started in few lanes of the toll plaza. The total length of the toll road is 52.46 Km having 12 lanes at the toll booth. Two lanes on each side of the toll are dedicated for the toll charge collection through radio-frequency identification (RFID) tag, i.e., Fast Tag for all the vehicles. The heavy traffic and larger waiting delays impair its functionality for which, the study focuses on analyzing the most appropriate payment method within the available design to minimize the queue length and minimum waiting time of users.

2.1 Data Collection

The toll plaza windows receive all the payments at the specific windows. The Fast tag is available at the two lanes, and three lanes are used for the toll collection through cash/card payment. However, one lane is defined for the exempted vehicles, as shown in Figure 2. The data had collected from the toll for all days of October, 2020, and it was observed that cash and Fast tag are the first choice of the drivers to pay the toll. However, long queues are formed during peak hours. It is evident from figure 3 that private passenger cars hold a significant portion of about 85% of the total traffic.

Fig.1 Aerial view of the toll plaza at Delhi-Rohtak highway from 50 m elevation

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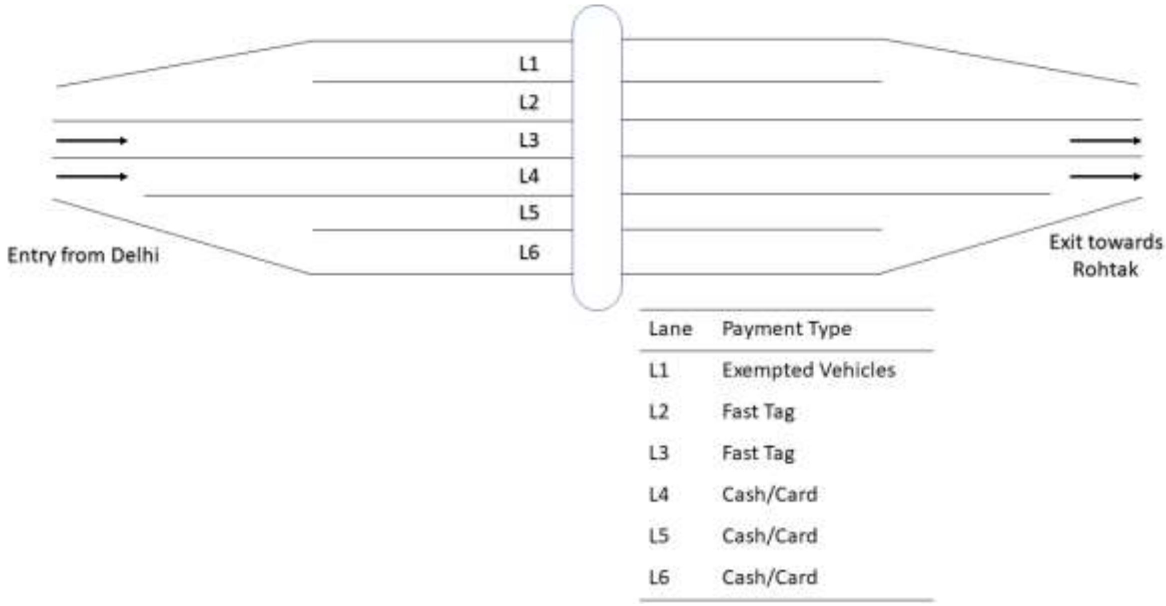

Fig.2 Schematic representation of toll plaza with payment wise lane types

The private cars hold 85% of total traffic, and the rest 15% is divided into another vehicle type such as a light commercial vehicle (LCV), heavy commercial vehicle (HCV) majorly buses and trucks and multi-axle vehicle (MAV) 3 axle and 4 axles vehicle travel through the study area. It was also observed from the data larger vehicle prefer fast tag. Moreover, heavy vehicles also prefer to complete their journey through Fast-Tag, as shown in Figure 3.

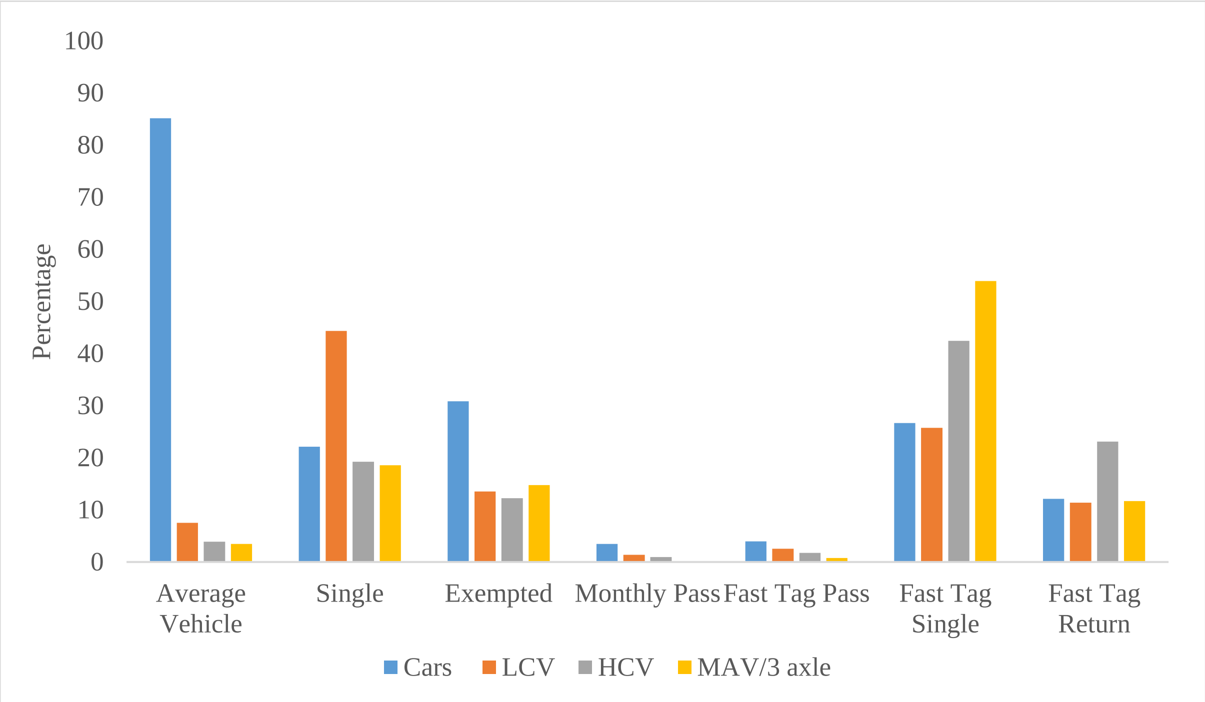

Fig.3 Description of data for various vehicle type

3. Methodology

Designing a toll plaza incorporates the optimized building of specific three zones as queueing area, toll booths, and merging area, including the study of vital features as number and type of tollbooths and the queue length in the queueing area upstream to the toll booths. The designing of a toll plaza involves determining specific parameters as the

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number of toll lanes, the relative distribution of manual and automatic toll lanes, and upstream queue length to prevent vehicle's overcrowding. The criteria for designing the toll plaza are based on the queue length and average waiting time users face at the toll plaza. Following maximum queue length criteria, the design parameters should be selected so that the probability of a queue length higher than the user-defined maximum should be below a threshold value [22]. The average waiting time is a deterministic quantity that defines its direct application in obtaining the parameter where the average waiting time should be considered below the user-defined threshold time. In the study, we estimated the number of toll lanes using maximum queue length and waiting time criteria.

The queue length acts as a deterministic factor for vehicle placement and categorizes the driver's specific selection for a smooth run with minimum delays. The simulation study requires the complete design of toll plaza geometry for the analysis of traffic flow. The simulation model designed for the study is shown in Figure 4. The satellite image of Delhi – Rohtak toll plaza was captured at 50 m elevation and uploaded into VISSIM 8.0 for the design of the toll plaza. The number of lanes, each lane's size, and the payment method available at each lane are the key input to any model. These data are incorporated from the satellite image, and the layout plan is designed. In the next step, the payment type is entered for each lane, and the driver pattern of selecting the lanes is entered in the software to complete the model configuration.

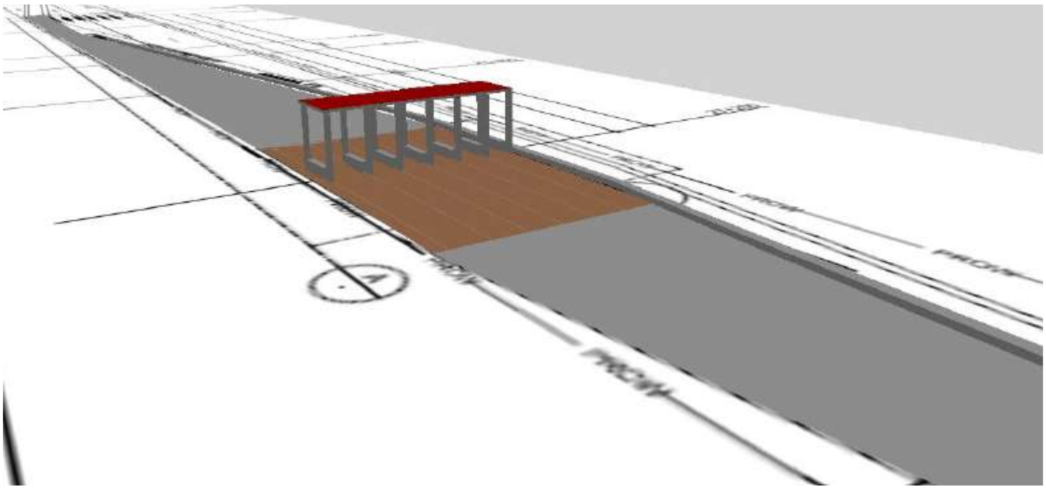

Fig.4 Model of toll plaza for simulation

The calibration of the simulation model is required to identify the similarity between the modeled and actual scenarios. The significant parameters like design speed of the road, number of approach lanes, type of vehicles, payment type at lanes, traveling time of each vehicle from the toll window, etc., are entered in the software. Figure 2 shows the toll plaza's conceptual model with the mode of payment accepted at the lane. After the calibration of the model, the simulation is performed with different traffic volumes. The model performance is observed at the traffic volume from 800 to 1300 vph (vehicle per hour). The traffic volume for each vehicle type is categorized from the base data.

4. Results and Discussion

The efficacy of the proposed model was evaluated after calibrating the simulation results through validation. It also assisted in parameter selection for designing toll plaza. The results of the study are categorized for different traffic volumes and vehicle types. The total traffic approaching toll contains passenger cars, two-wheelers, commercial vehicles (heavy and light), multi-axle vehicles, etc. The simulation is performed in two categories, including two-wheeler and passenger cars in LMV, and other lights and heavy commercial vehicles are categorized in the Non-LMV section. However, traffic is simulated in 800, 900, 1000, 1100, 1200, and 1300 vph of traffic density. The traffic volume is identified considering increasing traffic density for upcoming years and reducing traffic congestion at the toll plaza. The simulation results are shown in Tables 1 and 2 for LMV and non-LMV vehicles, respectively.

Table 1: Traffic simulation results of LMV crossing toll through a different payment type

Traffic Volume	Fast-Tag		Cash		Exempted	
	Traffic Volume	Length	Traffic Volume	Length	Traffic Volume	Length
800	372.54	0.68	178.55	3.36	248.91	0.72
900	419.10	1.03	200.87	6.32	280.02	0.99
1000	465.67	1.51	223.19	13.09	311.14	1.31
1100	512.24	2.18	245.51	32.52	342.25	1.72
1200	558.80	3.10	267.83	162.27	373.37	2.23
1300	605.37	4.43	290.15	334.32	404.48	2.87

Table 2: Traffic simulation results of Non-LMV crossing toll through a different payment type

Traffic Volume	Fast-Tag		Cash		Exempted	
	Traffic Volume	Length	Traffic Volume	Length	Traffic Volume	Length
160	87.22	3.01	51.11	3.62	21.67	0.72
180	98.12	4.77	57.50	6.00	24.38	0.99
200	109.02	7.39	63.89	9.90	27.09	1.31
220	119.92	11.64	70.28	15.82	29.80	1.72
240	130.82	18.65	76.67	25.49	32.51	2.23
260	141.73	32.30	83.06	43.50	35.22	2.87

Table 3: Total traffic simulation results crossing toll through a different payment type

Traffic Volume	Fast-Tag		Cash		Exempted	
	Traffic Volume	Length	Traffic Volume	Length	Traffic Volume	Length
960	459.75	3.69	229.67	6.98	270.58	1.45
1080	517.22	5.80	258.37	12.32	304.40	1.98
1200	574.69	8.90	287.08	23.00	338.23	2.62
1320	632.16	13.82	315.79	48.34	372.05	3.44
1440	689.63	21.74	344.50	187.76	405.87	4.46
1560	747.10	36.73	373.21	377.82	439.70	5.74

The number of lanes available for Fast Tag payment, cash/credit, and exempted vehicles is two, three, and one. The graphical representation of the queue for different vehicle types is shown in Figures 5 and 6. Scenarios in Figures 5 and 6 represent traffic volume selected for simulation where scenario 1 is 800 vph, and scenario 6 is 1300 vph for LMV. Similarly, scenario 1 is 160 vph, and scenario 6 is 260 vph for non-LMV. Figure 4 shows that traffic volume and mode of payment induces a significant impact on the queue length. As the traffic volume increases above 1100 vph, where the number of vehicles that pass-through cash lanes is only near about 250 vph, the queue length increases sharply. That indicates that the approaching vehicle is more than the lanes' carrying capacity for the cash transaction. However, a minimal queue is observed for Fast Tag and exempted vehicle a less time is required for the vehicle to cross the toll booth with the Fast tag payment option. The number of vehicles using the Fast tag is twice the number of vehicles using cash/card payment, which still does not form the queue.

Similar scenarios were designed for Non-LMV vehicles where scenario 1 represents 160vph, and scenario 6 represents 260vph. The number of vehicles using the Fast tag is more than the vehicles using cash/card-based payment options. The queue length from the cash lanes is more than the Fast tag; however, the fast tag's queue length from Non-LMV is bigger than the LMV vehicle due to the greater length of the vehicles.

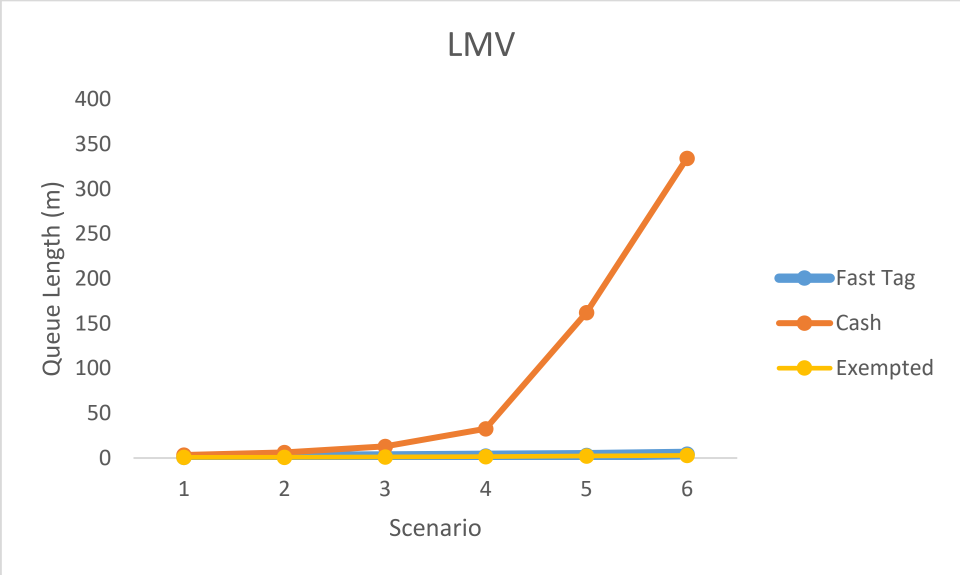

Fig.5 Queue length of LMV for different payment modes

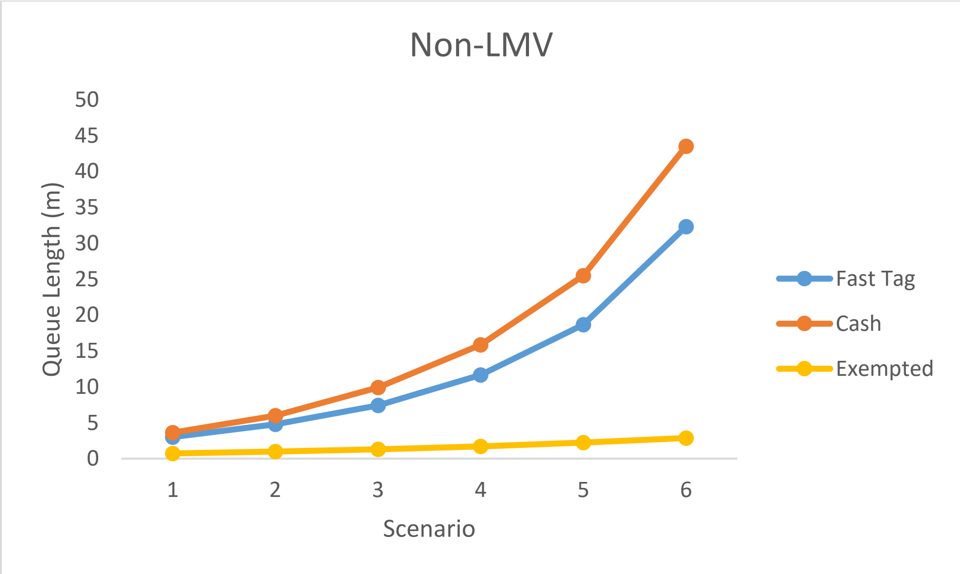

Fig.6 Queue length of Non-LMV for different payment modes

The cumulative traffic due to all the types of vehicle is shown in Table 3. The significant increase in the queue length of cash lanes were observed when traffic rises above 1300 vph and upto the maximum simulated density (1560 vph) the queue length reaches up to 373.21 m. The horizontal distance, i.e., approaching area to the toll plaza, is near about 230 m; however, as per the simulation studies, the queue length can reach up to 334.32 m also with the total traffic volume of 1300 vph, which would affect the movement of other vehicles also that are interested in other payment options. The results directly indicate the benefits of using Fast- Tag over cash payment, as the queue length in Fast-Tag was one tenth to the cash lane. With the increase in traffic also, the rate of growth of queue is much slower in Fast-Tag in comparison to cash lanes.

5. Conclusion

Maintenance of steady traffic flow of toll plaza is the significant prerequisite for the toll plaza's effective functioning. There is a stringent need to study and evaluate toll lanes' development and management with ease flow of vehicles without waiting delays. The simulation studies' application shows its broad applicability and has been used to simulate the traffic at Delhi-Rohtak toll plaza. The simulation is performed in 6 different scenarios with varying traffic volume for both the LMV and non-LMV category of vehicles. The model is calibrated and validated on the data collected for 30 days using VISSIM 8.0 model, and the validation studies demonstrated the model's reliable and realistic approach as the probability distribution appeared with the nearest proximity with validated results. The model's application as toll plaza designing is also studied after evaluating the number of toll lanes depending on minimum queue length and minimum waiting time criteria. The proposed analysis concluded with the efficient functioning of the model to be utilized for toll plaza designing.

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