

Traffic operations at mainline toll plazas

Chintaman Santosh Bari¹, Satish Chandra², Ashish Dhamaniya^{1,*} and Yogeshwar Navandar³

¹Department of Civil Engineering, SVNIT Surat, Surat 395 007, India

²Department of Civil Engineering, IIT Roorkee, Roorkee 247 667, India

³Department of Civil Engineering, NIT, Calicut 673 601, India

Most projects across the world are built under the public–private partnership (PPP) module. In the highway sector, the highway projects are built by the concessioner, and in lieu of that, he generates revenue by collecting tolls from road users. The toll plazas built across the highways to collect tolls act as a bottleneck in highway facilities. Although the toll collection system has been improved worldwide, users are still experiencing an enormous delay at toll plazas due to congestion, especially in developing countries like India. This congestion is caused due to various factors such as long service time, an inadequate number of windows, traffic volume, categories of toll rates, etc., which lead to delay, degradation of capacity, and level of service. Different researchers in their countries have analysed all these factors. The present article gives a detailed literature review summarizing various studies on the different parameters related to toll plazas and proposes research gaps from the perspective of developing countries. The challenges and methodology for evaluating various parameters are also discussed, and a way forward for future research is suggested.

Keywords: Capacity, level of service, mixed traffic, toll collection, toll plaza.

UNDERSTANDING traffic characteristics at toll plazas has a long historical perspective since the early 1950s. Many researchers have evaluated various parameters affecting toll plaza performance, capacity and level of service (LOS) during the last seven decades. The capacity of a section is a crucial term in the planning and designing of any traffic facility. It also acts as a tool to evaluate the operational conditions for the same facility. The main design element of a toll plaza is the number of toll lanes, which indirectly depends on the capacity analysis. Hence, the capacity aspect plays a vital role at the tollbooth as it provides the basis for deciding the number of toll lanes required during peak and off-peak hours to cater to the approach traffic volume at the toll plaza. Traffic in India and other developing countries is mixed and the same mixed traffic behaviour is observed at toll plazas (in the present study, the mixed traffic is devoted to the use of the same dedicated lane by various vehicle classes, causing the presence of

mixed vehicle nature in a particular toll lane). The mixed nature of traffic affects toll plaza operations in terms of increasing service time. Subsequently, users' waiting time in queue increases, which ultimately leads to a decrease in toll plaza capacity¹⁻³. The design guidelines for mid-block sections, highways, intersections, pavements and traffic analysis are given properly and are followed for uniformity throughout the nation⁴⁻⁶. However, the toll plazas are still designed as per the previous experience of the designer or a consultant. Therefore, design criteria for toll plazas vary from agency to agency. Further, due to mixed traffic conditions in toll lanes, the number of vehicles passing through a tollbooth in terms of vehicles/hour will not give proper insight to field engineers on the operating efficiency of toll lanes to satisfy the approaching traffic demand. Hence, the concept of equivalency factors in the line of Passenger Car Units (PCU) for highways and intersections is a vital aspect of converting a mixed traffic flow into a homogenous equivalent.

The LOS is a quality measure that describes the performance state of traffic flow. These conditions are converted into operational parameters directly related to the user's perception of comfort and convenience when travelling through different traffic scenarios⁷. As no explicit procedure was available for evaluating LOS at toll plazas, many researchers attempted to study LOS at toll plazas over the last few decades under various conditions in different parts of the world. However, due to the consideration of different measures of effectiveness such as volume to capacity (v/c) ratio^{8,9}, service time¹⁰, delay¹¹, etc. the scales of service for representing the performance of the toll plazas also depict a wide variation. Hence, capacity, equivalency factors, and LOS are the three essential parameters considered in the present review.

The present article aims to present the current state of traffic flow characteristics at toll plazas and identify and further explore crucial gaps experienced by various researchers across the world. The present study provides the background for analysing the traffic operations at toll plazas in developed and developing countries based on available literature. The study also provides a framework for researchers to focus on critical gaps.

To better appreciate the discussion in the article, the terms related to toll plazas need to be explained and understood.

*For correspondence. (e-mail: adhamaniya@ced.svnit.ac.in)

(1) Throughput: It is defined as the number of vehicles passing over a short period (usually one hour) through the toll plaza¹².

(2) Service time: Service time is defined as the exact time required by a vehicle to pay the toll at the tollbooth, excluding the waiting time in queue^{3,12}.

(3) Service headway: The time difference of exit of two consecutive reference points in the same toll lane is called a service headway. The service headway implies that headway at a toll plaza includes inter-arrival and service times for a given vehicle¹³.

(4) Clearance time: It is the time taken by the follower vehicle in the queue to arrive at the tollbooth after the leader vehicle completes its transaction procedure and exits^{14,15}.

(5) Waiting time in the queue: The time difference between when a vehicle joins the queue and enters the system to pay the toll fee¹⁶.

Methodology

Kitchenham¹⁷ defines systematic literature review as ‘a means of identifying, evaluating and interpreting all available research relevant to a particular research question, topic area, or phenomenon of interest’. The present study adopts the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) methodology for the systematic review. PRISMA is a set of reporting guidelines consisting of a checklist of twenty-seven items¹⁸. It was developed by the 29 review authors in 2009 (ref. 19). The PRISMA methodology was updated in 2020 (ref. 20) and is used in the present study.

Information sources

Based on the author’s search, no literature review paper was available on the current topic, and hence the present study is not an advancement; instead, it acts as a base review paper in the toll plaza traffic operations field. The articles from the peer-reviewed databases such as Scopus, Transport Research International Documentation (TRID), Web of Science (WOS) and ScienceDirect alone were considered to ensure the incorporation of the highest quality of research findings in the present review. All the datasets were obtained in the Research Information Systems (.ris) format.

The initial search was conducted for data up to November 2021. The data from 1954 to 2021 was retracted from different sources, and the inclusion and exclusion at each stage were carried out with the help of the Excel spreadsheet. For the initial data search, different key terms such as ‘toll plaza’, ‘toll plazas’, ‘capacity’, ‘level of service’ were used. The search was carried out with the use of different Boolean operators such as ‘toll plaza’ OR ‘toll plazas’, ‘toll plaza’ OR ‘toll plazas’ AND ‘capacity’, ‘toll

plaza’ OR ‘toll plazas’ AND ‘level of service’ and ‘toll plazas’ AND ‘level of service’ AND ‘capacity’. The search keyword is applied only for TITLE, ABSTRACT and KEYWORDS. These searches resulted in 1093, 370, 617 and 50 articles from Scopus, WOS, TRID and ScienceDirect respectively.

Screening phase (inclusion and exclusion of the articles)

The main aim of the study is more focused on the engineering point of view. Hence the first filter of exclusion, i.e. articles published in the medical sciences, radiology, etc., were excluded. No year filter was applied as the paper is a first-of-its-kind review paper on toll plaza operations. Further, the second criterion for inclusion filter was applied, and thus the research articles, conference proceedings, and book chapters were included in the present study. Only the ‘ENGLISH’ language documents were included. Finally, the studies relevant to the capacity and LOS were screened from the remaining articles using the boolean operators.

Eligibility and exclusion of duplicate articles

Before the eligibility process, duplicate articles were removed using the spreadsheet. After removing the duplicates from all datasets, 610 documents remained. After the eligible articles, the documents with full-text access alone were considered. Then, the manual screening of each document led to the final documentation of about 59 articles. Additionally, the 15 articles were identified by a bibliographic search, mostly including the National Cooperative Highway Research Program (NCHRP) reports, Indian Roads Congress (IRC) Codes, etc. on toll plaza operations. Finally, a total of 74 articles were considered for the analysis.

Results

About 74 studies considered in the present review dealing with the capacity and LOS-related parameters on toll plazas were published from 1954 to 2021. About 52% of studies were carried out in the homogeneous traffic conditions primarily observed in the developed countries and only 34% of the studies were focused on mixed traffic issues.

The research on toll plaza operations started way back in 1954, with the first classical paper by Edie on manual toll operations. Motivated by this paper, various studies were started in developed countries; however, the research rate observed from publications was merely 1996 (less than 10 percentile). Consequently, researchers started to explore the benefits of electronic toll over manual toll; hence the number of publications was slightly higher until 2011. Later, an increasing trend in research, mostly for mixed traffic conditions is seen from 2018 to 2021

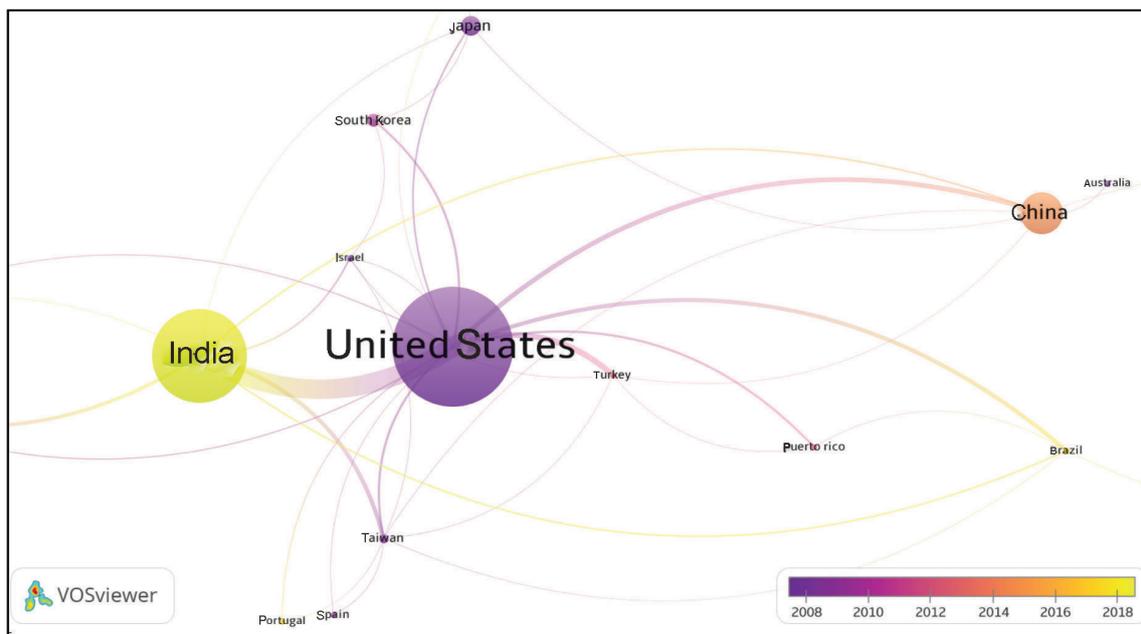


Figure 1. Cluster graph showing the country-wise variation of research.

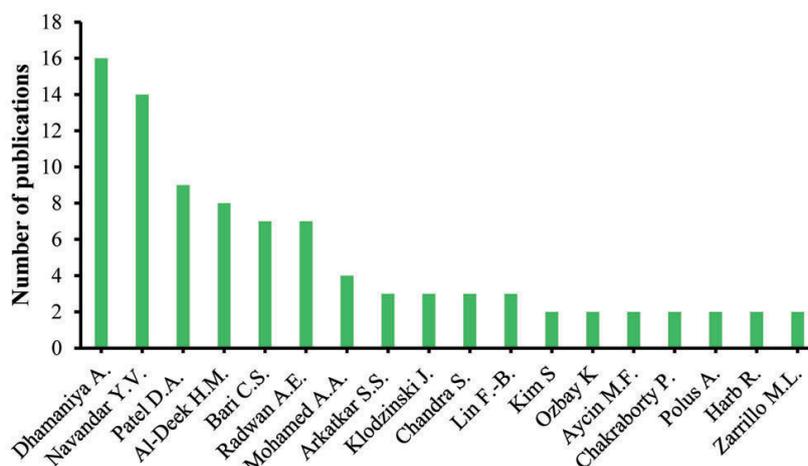


Figure 2. Author wise distribution.

(30 percentile of the papers were published in these years). Figure 1 shows the cluster graph for the distribution of research for different countries around the globe developed using VOSviewer software²¹.

It can be seen that the United States of America (USA) has a higher number of publications, followed by India and then China. About 36% of the total considered publications were from the USA, and about 28% were from India (Figure 1). Figure 2 illustrates the author-wise distribution of publications considered for having a minimum of two articles. A total of 122 researchers contributed, considering the 74 publications. A total of 102 researchers have only a single publication. It can be seen that A. Dhamaniya is the most prolific researcher in the area of toll plaza traffic operations,

with a total of 16 publications. He is followed by Y. Navandar (14 articles), D. Patel (9 articles), and Al-Deek (8 articles). One point to note here is that Al-Deek was a pioneer in working on toll plaza operations and published much research before 2005, but on homogeneous traffic conditions.

Parameters considered in the literature

The capacity of the toll plaza

The capacity of any facility can be defined as the maximum number of persons or vehicles reasonably expected to

traverse at a point or a uniform section of a lane or roadway during a given period under the prevailing roadway, traffic, and control conditions⁷. The capacity of a section is the key term in planning and designing any traffic facility. It also acts as a tool to evaluate the operational conditions for the same facility.

Eddie²² conducted preliminary work using empirical data to determine the number of toll booths and toll collectors scheduled on the Lincoln tunnel based on the probabilistic analysis. This study portrayed methods for determining the relationship between traffic volumes, delay and the number of tollbooths. Schaulfer²³ collected field data from 54 toll plazas in the United States. The author found that the optimal capacity is achieved when the eight queued vehicles are waiting to get served. According to survey results, the manual lane's average capacity was 416 vehicles per hour per lane (vphpl) for passenger car traffic only which decreases up to 360 vphpl for mixed traffic (presence of less than 5% trucks or buses). On the other hand, for ETC lanes, the average capacity is 1154 vphpl for passenger cars and 1050 vphpl for mixed traffic (presence of less than 5% trucks or buses). He found the capacity of express ETC lanes to be 1500 vphpl for passenger car traffic only. Zarrillo²⁴ proposed equations for capacity estimation of toll plazas as

$$C = J + K_{MTE}, \quad (1)$$

where C is the toll plaza capacity (vph), J the capacity of single service lanes (vph), K_{MTE} is the capacity of mixed-use lanes (vph) calculated as

$$K_{MTE} = N_{MTE} S_{MTE} = N_{MTE} \frac{100\%}{\frac{P_M}{S_M} + \frac{P_T}{S_T} + \frac{P_E}{S_E}}, \quad (2)$$

where K is the capacity of mixed-use lanes (vph), N the number of lanes for mixed-use, S_i the vehicle processing rate for payment type- i (vph), P_i the percentage of vehicles utilizing payment method, i.e. M for manual lane, T for mixed lane and E for ETC lane.

Aycin²⁵ developed a methodology for determining toll plaza capacity by considering the approach roadway conditions and traffic demand characteristics. This methodology appears suitable for manual calculation and is suggested to improve users' understanding of toll plaza operation. The author proposed eqs (3)–(6) for capacity estimation considering different tollbooths payment options.

$$C_{ETC} = 3600 \frac{V_{ETC}}{S}, \quad (3)$$

$$C_{cash} = \frac{3600}{\text{Service time} + \text{moveup time}}, \quad (4)$$

$$C_{\text{cash-ETC}} = \frac{3600}{\sum_j \Delta t_j P_j}, \quad (5)$$

$$C_{\text{plaza}} = N_{\text{cash}} \times C_{\text{cash}} + N_{\text{ETC}} \times C_{\text{ETC}} + N_{\text{cash-ETC}} \times C_{\text{cash-ETC}}, \quad (6)$$

where C_i is the capacity of tollbooth for payment type i (vph), V_{ETC} the average ETC vehicle speed (feet/s), S the average distance headway (feet/veh), Δt_j the transaction time of pair- j , P_j is the probability of possible leader-follower pairs given the percentage of ETC vehicle using the mixed lane.

Li²⁶ carried out the capacity analysis of the ETC lanes and developed equation depending upon the service time.

$$C = \frac{3600}{T_S + T_G \times k}, \quad (7)$$

where C is the ETC lane capacity, T_S the standard car service time, T_G the standard car leaving time, k is the standard car adjustment coefficient (taken as 0.7).

Indian Road Congress (IRC)²⁷ suggests the capacity of 240 vph for manual and automated toll booths and 1200 vph for ETC lanes. Navandar *et al.*²⁸ determined the capacity of the MTC lanes operating under mixed traffic conditions in tollbooth equivalency factors (TEFs). The latest study by Bari *et al.*²⁹ studied the capacity of ETC lanes in Indian mixed traffic conditions. Table 1 describes the Strobe list table showing the different parameters considered in the literature for capacity analysis.

From the above description, it can be seen that no single method is universally accepted for capacity estimation at toll plazas. However, various researchers have tried different methods according to the field conditions. Most methods used the service headway or the service time as the parameter for the capacity estimation. The equation given by Aycin²⁵ consists of speed, service time, and clearance time, which can be a good estimator of the capacity of toll plazas. Further, Aycin²⁵ has given the capacity estimation formulas for different leader-follower pairs of MTC and, ETC vehicles. So, one can apply the equation for getting the capacity for traffic consisting of only passenger cars and heavy vehicles. Limited studies are for mixed traffic conditions; so it is necessary to consider capacity estimation.

Level of service at the toll plaza

LOS is a quality measure that describes the performance state of traffic flow. These conditions are converted into operational parameters directly related to the user's perception of comfort and convenience when travelling through different traffic scenarios⁷. As no explicit procedure was available for evaluating LOS at toll plazas, many

Table 1. Literature related to capacity

Researcher	Parameter										Country
	TOL	ST	SH	CT	D	SIM	Q	DIS	PCU	HO/HT	
Edie ²²	M	X			X			X		HO	USA
Al-Deek <i>et al.</i> ⁴⁹	M, E	X	X	X	X			X		Any	USA
Polus and Reshetnik ⁵⁰	M, E									HO	USA
Al-Deek <i>et al.</i> ⁵¹	M, E	X	X	X	X			X		Any	USA
Polus ⁵²	M, A, E	X			X	X				HO	USA
Boronico and Siegel ⁵³	M	X			X					HO	USA
McDonald and Stammer ⁵⁴	M, A, E	X								HO	USA
Astarita <i>et al.</i> ⁵⁵	M, A, E	X			X	X				HO	Canada
Perry and Gupta ⁵⁶	M, E	X			X	X				HO	USA
Al-Deek ⁵⁷	M, A, E	X			X	X		X		HO	USA
Lin ⁵⁸	M				X	X				HO	Taiwan
Klodzinski and Al-Deek ⁵⁹	M, A, E	X			X	X		X		HO	USA
Zarrillo <i>et al.</i> ⁶⁰	M, A, E					X				HO	USA
Al-Deek <i>et al.</i> ⁶¹	M, A, E	X			X	X		X		HO	USA
Aycin ²⁵	M, E	X	X	X	X					HO	USA
Upchurch ⁶²	M	X	X	X						HT	USA
Zarrillo and Radwan ⁶³	M, E						X			HO	USA
Kim ⁶⁴	M, A, E				X	X	X			HO	Korea
Shitama <i>et al.</i> ⁶⁵	M, E	X	X		X	X		X		HO	Japan
Kim ⁶⁶	M, E					X				Any	USA
Gugol <i>et al.</i> ⁶⁷	E	X			X	X	X			HT	Philippines ⁷
Li ²⁶	E	X				X				HO	China
IRC ^{4,27}	M, E	X	X							Any	India
Bains <i>et al.</i> ⁶⁸	M	X				X				HO	India
Chang <i>et al.</i> ⁶⁹	M	X			X		X			HO	China
Zhang <i>et al.</i> ⁷⁰	E					X				HO	China
Navandar <i>et al.</i> ²⁸	M	X	X	X				X	X	HT	India
Talavirya and Laskin ⁷¹	M, E	X					X	X		HO	St Petersburg
Bari <i>et al.</i> ²⁹	M, E	X							X	HT	India

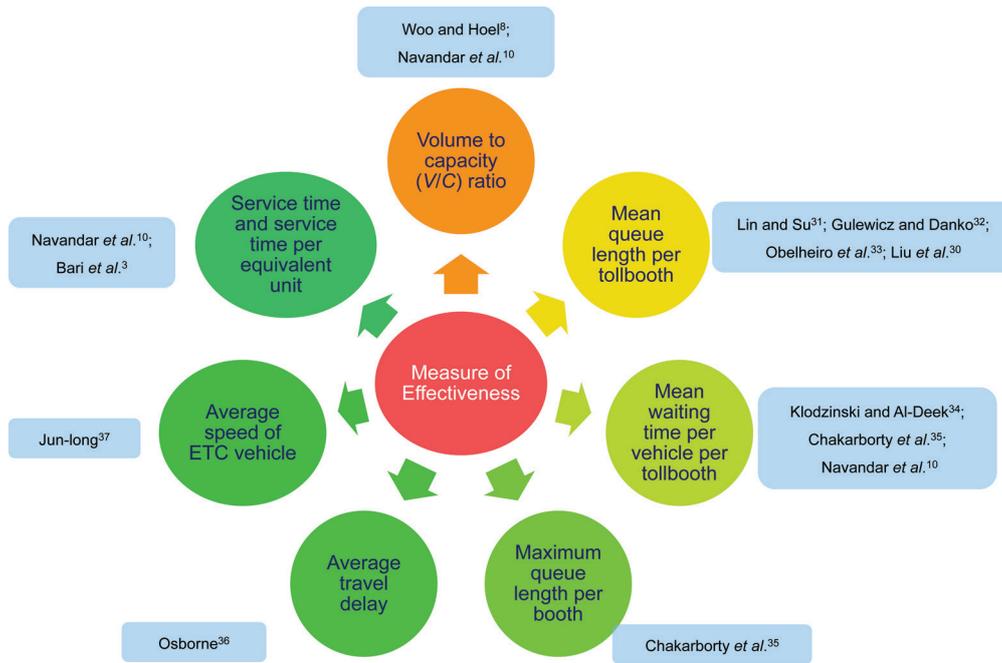
TOL, Type of lane; M, MTC lane; A, Automatic coin machine (ACM) lane; E, ETC lane; ST, Service time; SH, Service headway; CT, Clearance time; D, Delay; SIM, Simulation; Q, Queuing; DIS, Distribution; PCU, Passenger car unit; HO, Homogeneous traffic; HT, Heterogeneous traffic.

researchers attempted to study LOS at toll plazas over the last few decades under various conditions in different parts of the world. However, due to the consideration of different measures of effectiveness (Figure 3), the scales of levels of service for representing the performance of the toll plazas also depict a wide variation. As seen from Figure 3, researchers have taken *V/C* ratio^{8,9}, mean queue length per booth³⁰⁻³³, mean waiting time per vehicle per tollbooth^{10,34,35}, mean waiting time for the entire toll plaza³³, maximum queue length per tollbooth³⁵, average travel delay³⁶, average speed of ETC vehicle³⁷, and service time and service time per equivalent unit^{3,10}.

A study by Klodzinski and Al-Deek³⁴, considered 85th percentile individual delay at toll plazas as MOE for defining LOS thresholds. Obelheiro *et al.*³³ proposed different LOS criteria in context with the users' perception. They evaluated LOS for toll plazas located in Brazil using field and VISSIM simulated data. The average queue length and the percentage of trucks present in the queue were taken as LOS indices. The queue length at the tollbooth was found to be the most influencing factor for users' perceived level of service. Further, the LOS thresholds were compared with the users' perceived service time and

delay. Navandar *et al.*¹⁰ revealed the LOS thresholds based on service time, service headway and waiting time in the queue. Navandar *et al.*³⁸ provided the LOS thresholds under mixed traffic conditions using an ordered probit model for MTC in another study. The authors found that the humps at the tollbooth were one of the most influencing factors affecting LOS. Table 2 illustrates the different studies primarily focused on LOS at toll plazas.

Similar to the capacity analysis, it is observed that the LOS thresholds are not fixed for toll plazas and are not given in the referred guidelines such as Highway Capacity Manual (HCM)³⁹ and Indo-HCM⁵. Researchers used different parameters to determine LOS, such as delay, service time, service headway, *V/C* ratio, average queue length, etc. The service time, service headway, and *V/C* ratio are point measures, but, on the other hand, delay and queue length is space measure, and hence, it can be seen that various researchers use the delay for determining LOS. This delay-based LOS can be related to the LOS thresholds developed for other facilities like intersections. The delay gives the level of discomfort and inconvenience to the users due to the toll plaza. Thus, it can be a good measure for determining the LOS than any other parameter.



Note: Numbers in superscript indicates the reference number

Figure 3. Different MOEs for LOS estimation reported in the literature.

Table 2. Literature studies for LOS at toll plazas

Researcher	Parameter						Country
	TOL	ST	D	SIM	DIS	HO/HT	
Klodzinski and Al-Deek ³⁴	M, A, E		X	X	X	HO	USA
Obelheiro et al. ³³	M			X		HT	Brazil
Inacio et al. ⁷²	M	X		X		HT	Brazil
Navandar et al. ^{38,73}	M					HT	India
Navandar et al. ¹⁰	M		X			HT	India
Bari et al. ³	M	X			X	HT	India

Combined study of capacity and LOS

The present section discusses the studies related to capacity and LOS combined. Woo and Hoel⁸ found that the capacity varies from 600 to 750 passenger cars per hour, depending on the toll collection method and traffic composition. For example, with a higher truck proportion, service time was found to be more, thus decreasing the service volume, whereas, for small vehicles, it was vice versa. It was observed that demand volume has significant effects on toll plaza capacities. Equation (8) was proposed for estimating the capacity of the entire toll plaza

$$\begin{aligned}
 C &= \sum_1^j n_j C_j = n_1 \frac{3600}{t_{i1}} + n_2 \frac{3600}{t_{i2}} + \dots + n_j \frac{3600}{t_{ij}} \\
 &= \sum_1^j n_j \frac{3600}{t_{ij}},
 \end{aligned}
 \tag{8}$$

where C is the capacity of toll plaza (vehicles/hour) (vph), n_j the tollbooth with collection type- j , C_j the capacity of toll booth with collection type- j (vph), t_{ij} is the service time for vehicle type i and toll collection type- j (s).

The authors statistically correlated the V/C ratio to the density in the arrival and departure areas of the plazas and concluded that the V/C ratio could be estimated from the density values. The average density was chosen as a performance indicator for the LOS.

Lin and Su³¹ used mean queue length at the tollbooths and meantime in the system to measure effectiveness for defining LOS. The delay-based LOS values given by Highway Capacity Manual for Taiwan Area⁴⁰ at intersections were used for defining the LOS based on the meantime in the system. They reported that the performance of a toll gate could be significantly affected by several factors such as service capacity, vehicle's arrival pattern, number of available gates, and drivers' behaviour.

Table 3. Literature studies for combined capacity and LOS at toll plazas

Researcher	Parameter									Country
	TOL	ST	SH	CT	D	SIM	PCU	HO/HT		
Woo and Hoel ⁸	M, A	X						HO	Virginia	
Lin and Su ³¹	M	X				X		HO	Taiwan	
Osborne ³⁶	M, A, E				X	X		HO	USA	
Zhong <i>et al.</i> ⁷⁴	M, E				X	X		HT	China	
Jun-Long ³⁷	E	X	X					HO	China	
Liu <i>et al.</i> ³⁰	M, E		X	X			X	HO	China	
Navandar <i>et al.</i> ⁹	M	X	X		X		X	HT	India	

Al-Deek *et al.*⁴⁹ suggested the theoretical measurement of capacity based on inter-vehicle time as shown

$$Capacity = 3600/T_i, \tag{9}$$

where T_i is the inter-vehicle time measured during a peak 20-minute of the period.

The evaluation results showed an increase in maximum throughput by 154% for dedicated AVI lanes. Osborne³⁶ took simulation-based capacity estimation attempt in FREEPLAN. The developed equations are

$$Cap = \frac{3643.564 \times N}{\bar{t}_{process}} - 1.313 \times PctTrucks, \tag{10}$$

where Cap is the maximum number of vehicles a toll plaza can discharge per hour (veh/h), $\bar{t}_{process}$ the average processing time for the plaza (s), N the number of open toll lanes, $PctTrucks$ is the percentage of trucks present.

A study from China by Jun-Long³⁷ focused on the analysis of ETC traffic flow and their characteristics and developed the basic capacity formula of an ETC channel is given

$$C_b = k \frac{3600}{t_0} = k \frac{1000V_0}{l_0} = k \frac{1000V_0}{\frac{V_0}{3.6} + \frac{V_0}{254\phi} + l_v + l_{sv}}, \tag{11}$$

where l_v is the average vehicle length (generally 6 m), l_{sv} the safe distance between the vehicle (2 m), ϕ the longitudinal adhesion coefficient between tier and road adhesion coefficient, C_b the basic traffic capacity of the road, V_0 the driving speed, t_0 the minimum headway, l_0 the smallest front spacing, k is the influence coefficient. He developed the different service level criteria based on the delay faced by ETC vehicles.

The capacity and LOS of the toll plaza operating under mixed traffic conditions are examined by Liu *et al.*³⁰ in China. The LOS for toll lanes is defined based on average queue length and V/C ratio. Navandar *et al.*⁹ studied the capacity and LOS for manual tollbooths operating under mixed traffic conditions by considering the V/C ratio. Table 3 shows the parameters considered by different res-

earchers for the combined study of capacity and LOS at toll plazas.

The method of capacity determination by Jun-Long³⁷ was found to be more complex as it involves various parameters. On the other hand, the method suggested by Osborne³⁶ is simple and easy to apply in traffic conditions having only cars and trucks. Further, the LOS estimation is carried out by various methods for toll facilities, and hence, there is a need to study it meticulously to come up with acceptable LOS standards.

Equivalency factor

The equivalency factor has been least studied till now as most of the available studies are from developed countries with homogeneous traffic conditions. However, in developing countries like India, the traffic is heterogeneous in the toll lane, which significantly affects the traffic operations, and therefore the necessity of an equivalency factor is felt. Woo and Hoel⁸ developed the vehicle equivalent factor depending upon the service headway. Liu *et al.*³⁰ developed the PCU based on average inter-vehicle time for vehicles in pairs. Navandar *et al.*²⁸ projected the new concept of tollbooth equivalency factor (TEF) based on service time and clearance time for manually operated tollbooths. The TEF is used to convert all vehicle classes in terms of SC.

$$TEF_i = \frac{ST_i / ST_c}{CT_c / CT_i}, \tag{12}$$

where ST_i and ST_c are the service time for vehicle type- i and standard car respectively; CT_c and CT_i are the 85th percentile clearance time of the standard car and vehicle type- i respectively.

Table 4 shows the comparison of equivalency factors for different vehicle classes as reported in the literature. It is found that the values obtained by Liu *et al.*³⁰ are lower than those of other studies. The values of equivalency factors in the mixed traffic conditions^{28,29} are higher than those given for homogenous traffic conditions^{8,30} due to an increase in service time and clearance time.

Table 4. Comparison of the equivalency factors from the previous studies

Study	Parameters used	Type of lane	Vehicle class				
			Light commercial vehicles (LCV)	Bus	Heavy commercial vehicles (HCV)	Multi axle vehicles (MAV)	Trailer
Woo and Hoel ⁸	Service headway	MTC	–	–	2.39–2.91	–	–
Liu <i>et al.</i> ³⁰	Service headway	MTC	–	–	1.03–1.27	–	–
Navandar <i>et al.</i> ²⁸	Service time and clearance time	MTC	1.28–2.63	1.38–3.91	1.84–4.97	2.32–7.66	2.94–5.35
Bari <i>et al.</i> ²⁹	Service time	MTC	1.69	1.49	2.03	2.04	2.10
Bari <i>et al.</i> ²⁹	Service time	ETC	1.06	0.78	1.01	0.92	1.06

As observed, very few studies were reported to find the equivalency factors at toll plazas as most studies considered only passenger car traffic or only a few percentages of heavy vehicles. However, in developing countries like India, Sri Lanka, China, etc., the traffic consists of different vehicle classes. Thus to encounter their effect on any facility, the equivalency factors should be developed. Further, the developed equivalency factors are for MTC lanes, and thus there is a need to develop the same factors for vehicles using ETC lanes. The latest study by Bari *et al.*²⁹, proposed the average values of the vehicle class-wise equivalency factor for the ETC lane. As these developed equivalency factors do not cover the effect of traffic volume and traffic composition, there is a necessity to develop the same factors that encounter the effect of traffic volume and traffic composition.

Critical observations

The knowledge of the capacity of the toll facility will help to estimate the required number of toll lanes based on approach volume and traffic composition. Further, the LOS thresholds can provide the basis for performance evaluation of the toll facility by considering the service time, delay, etc. The main aim of the present study is to explore the capacity and LOS estimation methods and the gaps that need to be further reviewed soon. The following are the important findings of this review.

(1) Service time is one of the most critical parameters for the evaluation of the efficiency of the system. The lesser the service time, the more will be the capacity. Service time for MTC lanes varies with the vehicle classes, traffic composition, leader-follower pair, location, toll rate, drivers' seat height, drivers' and tollbooth operator' behaviour and type of payment⁸. The service time is found to be different under homogeneous traffic conditions and mixed traffic conditions.

The comparison of service time found in different studies is shown in Figure 4. For MTC, the service time varies from 2.05 to 35.56 sec for passenger cars. The average service time for the MTC system considering all vehicle classes is found to be 14.15 sec, having a standard deviation of 8.11 sec. The higher standard deviation of the

MTC values is observed due to higher service time values of the commercial vehicles and mixed traffic conditions. ETC service time was found to vary from 0 sec to a maximum of 10.44 sec for passenger cars. The average value of the ETC service time is 3.81 sec with a standard deviation of 2.05 sec (Figure 4).

(2) Various researchers deal with the capacity estimation of tollbooths for MTC and ETC lanes. The capacity is calculated by taking various measures of effectiveness, such as service time or saturation headway. The capacity of the manual lane was found to vary from 240 vph (ref. 27) to 705 vph (ref. 8), while for the ACM lane, it ranged from 425 vph to 687 vph (ref. 23). Mainly for the ETC system, the capacity of mixed AVI lane is 700 vph, dedicated AVI lane is 1200 vph, and express AVI lane is 1800 vph. The variation in capacity is observed due to the service time and headway variations. The various capacities obtained by different researchers are illustrated graphically in Figure 5. It can be concluded from Figure 5 that the average capacity of the MTC lane is 384 ± 142 veh/h/lane, for the ACM lane, it is about 557 ± 148 veh/h/lane and for ETC it shows the value of 1050 ± 412 veh/h/lane.

(3) The level of service of toll plaza facilities is of great interest to various researchers with different measures of effectiveness (MOE's), as discussed in Figure 3. Many of them focused on LOS based on the delay or waiting time in the queue. On comparing homogeneous traffic conditions with mixed traffic using MOE of waiting time in the queue, it is found that for LOS A, the minimum waiting time for the homogeneous condition is about 15 sec and that for mixed traffic, it is about 45 sec (Table 5). Thus, it can be concluded that the LOS standards are not fixed and may vary on traffic conditions and operations.

(4) Equivalency factors for vehicles at toll plazas are studied based on service headway, service time and clearance time. The ETC equivalency factors are lower than that of MTC lane equivalency factors.

Future directions

The following directions are proposed for further research to fill the gaps in the literature on the operations and design of toll plazas.

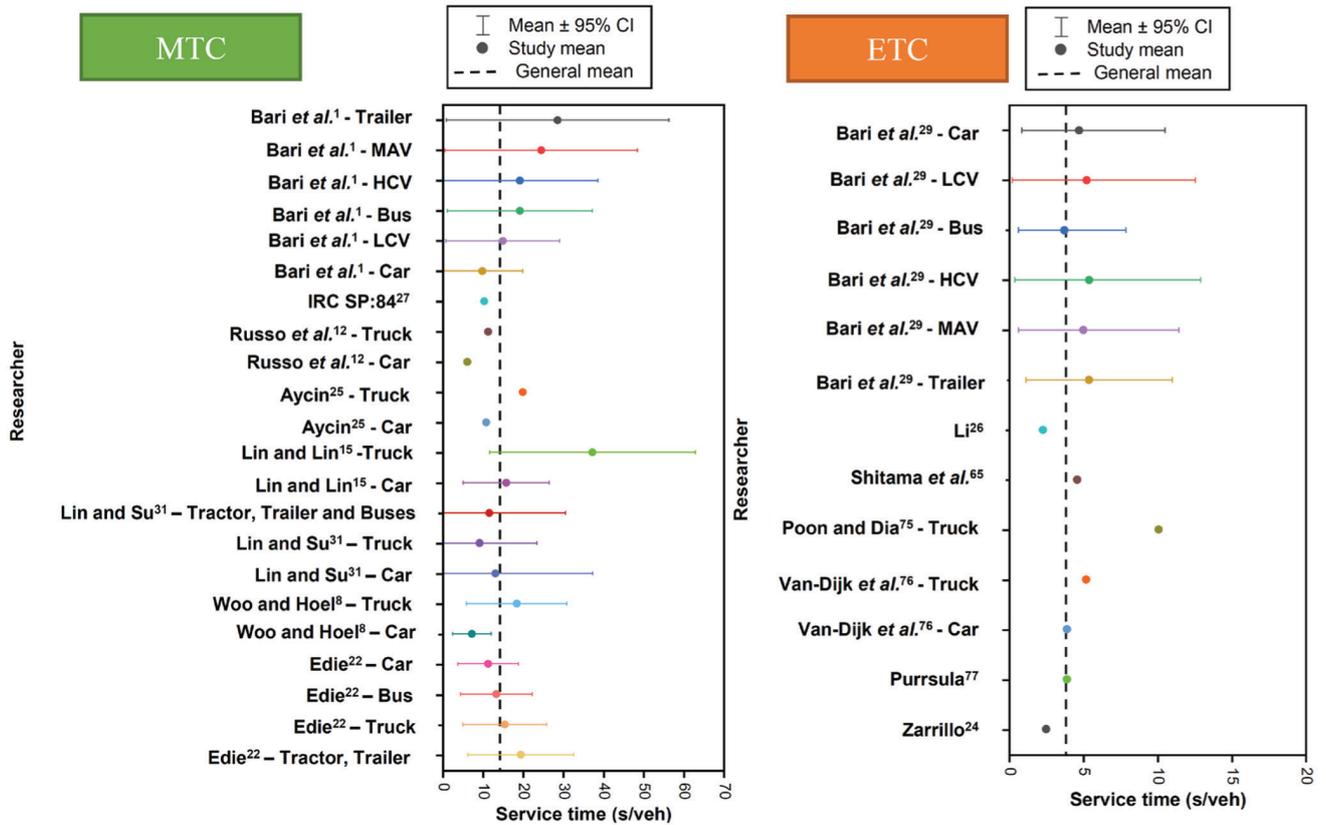


Figure 4. Service time in different studies for different toll collection systems.

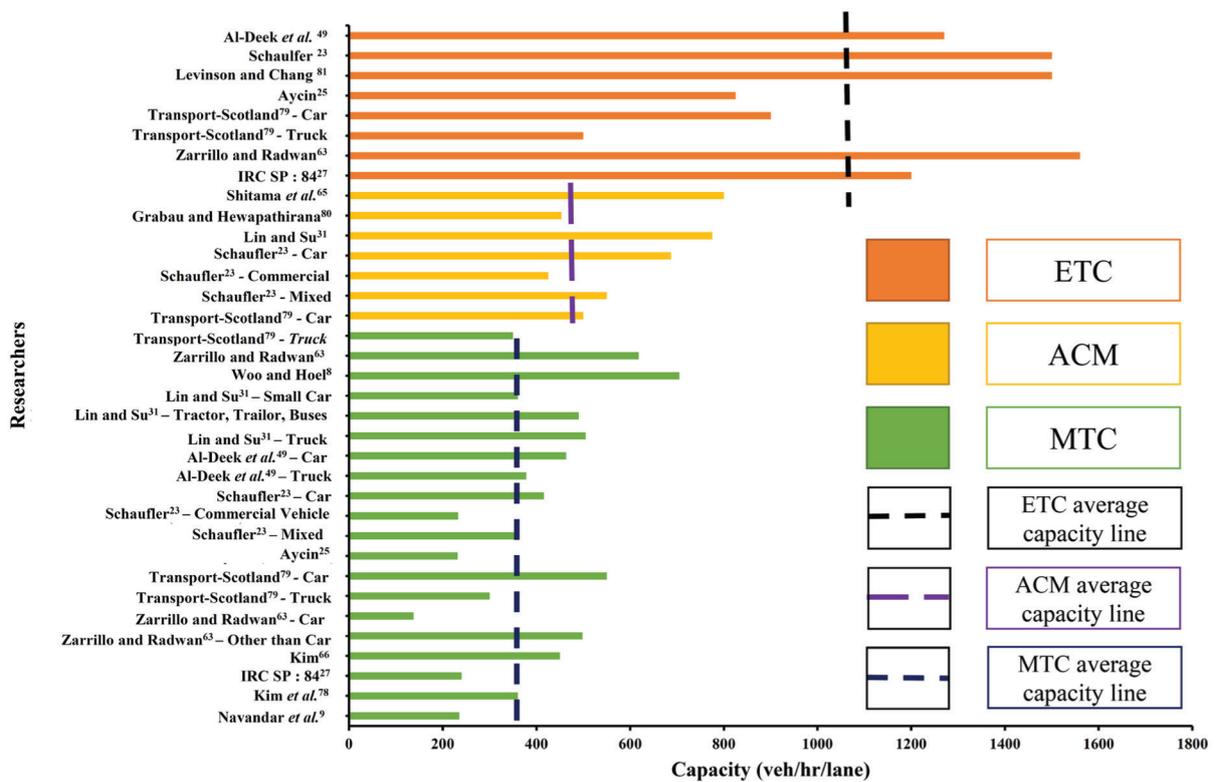


Figure 5. Capacity from literature for a different type of toll collection systems.

Table 5. Different LOS thresholds given in the literature

Authors	Country	Criteria	Level of service					
			A	B	C	D	E	F
40	Taiwan	Average stopped delay (s/veh)	<15	15–30	30–45	45–60	60–80	>80
8	Virginia	V/C ratio	<0.24	0.24–0.40	0.40–0.57	0.57–0.74	0.74–1.00	Not applicable
8	Virginia	Density (passenger car/mile/lane)	<12	12–20	20–30	30–42	42–67	>67
31	Taiwan	Average queue length in vehicles	<1	1–2	2–3	3–6	6–10	>10
31	Taiwan	Average time in system (s/veh)	<15	15–30	30–45	45–60	60–80	>80
34	USA	85th percentile delay (s/veh)	<14	14–28	28–49	49–77	77–112	>112
33	Brazil	Queue length (m)	≤3	3–11	11–27	27–58	58–134	>134
36	USA	Average travel delay (s/veh)	≤32	32–36	36–42	42–50	50–60	>60
37	China	Average delay (s)	<1.80	1.80–3.60	3.60–7.20	7.20–18	>18	Not applicable
37	China	Average speed (km/h)	20–30	15–20	10–15	5–10	<5	Not applicable
37	China	Service traffic volume (PCU/h)	300	450	700	900	1000	Not applicable
10	India	Waiting time in queue (s/veh)	<45	45–77	77–113	113–154	154–202	>202
10	India	Service time (s/veh)	<7	7–12	12–17	17–23	23–30	>30
10	India	Service headway (s/veh)	<13	13–18	18–25	25–33	33–43	>43
3	India	Normalized service time (s/TEFs)	<4	4–8	8–12	12–17	17–25	>25

(1) The service time characteristics of ETC lanes under mixed traffic conditions have not been studied yet. In most developing countries where the ETC system has been deployed in the last couple of years, the penetration rates are lower. The service time of ETC depends on the ability of the sensors to respond to the tag (like EZ Pass, M-Tag, FASTag, etc.), which further depends upon the position of the receiver and speed of the vehicles passing through the lane. The effect of the boom barrier on the service time is also not precisely evaluated in mixed traffic conditions.

(2) Service headway is the basis of capacity estimation for most studies. These are focused on the homogeneous traffic conditions or where the traffic consists of two classes of vehicles only (passenger cars and trucks). However, in many developing nations, the traffic conditions are mixed in nature; having more than two classes of vehicles in different proportions in the traffic stream creates heterogeneity in the service time and service headway properties due to different leader-follower pairs. Researchers give little attention to the service headway distribution under mixed traffic conditions for ETC lanes and hybrid lanes (MTC plus ETC vehicles allowed in a single lane).

(3) Different researchers suggest different capacities for various types of lanes depending on service time and service headway. Most studies derived capacities in homogeneous traffic conditions. Hence, it is necessary to develop the capacity equation considering the different proportions of the vehicle class in the traffic stream at the toll plaza to quantify the effect of different leader-follower pairs for ETC lanes. Further, the applicability of stochastic capacity or the capacity as the function of breakdown probability can be evaluated by taking the possible uncertainty in the datasets.

(4) Driving simulators should be used in the study to capture a driver’s human and psychological factors. Further, most simulation models assumed the distribution of service time and service headway from the literature for

homogeneous traffic conditions. It is suggested to study the distribution pattern of service time and service headway for mixed traffic conditions before using it in the model, mostly for ETC lanes.

(5) LOS criteria are mostly based on the delay’s field values with hardly any emphasis on the users’ perception. It should be considered in future studies. The comparison between users’ perceived and defined thresholds gives the ground truth of LOS. Based on the delay and queue length for mixed traffic conditions, warrants for the operation of ETC lanes based on upcoming traffic volume and traffic composition can be studied in the future.

(6) Equivalency factors are the basis for converting mixed traffic into homogeneous traffic. However, all the studies have either considered the vehicles as it is, or taken PCU from HCM to convert them into an equivalent number of cars. Traffic behaviour at toll plazas is different from other sections of the road. Therefore, comprehensive research is needed to develop PCU factors for different categories of vehicles at toll plazas. Further, the equivalency factors are mostly developed based on the point measures such as service time, service headway, etc. Thus an effort should be made to incorporate delay for developing toll equivalency factors as developed for signalized intersection⁴¹.

Apart from this, efforts should be taken for data collection methodology using drones, Wi-Fi/bluetooth sensors, etc. Trajectory data should be used to analyse micro parameters at toll plazas precisely. Drivers’ perceptions, toll-booth attendants, and toll plaza managers’ perceptions should also be studied to increase the efficiency of the toll facility. Acceleration and deceleration-based geometric design are required to enhance safety. Emission studies should focus on mixed traffic conditions and measures to mitigate them. Moreover, the study of high occupancy toll lanes (HOV), willingness to pay (WTP) for ETC lanes or HOV lanes, freight corridors and congestion pricing

strategies should be taken into consideration⁴². Now the world is moving toward connected and autonomous vehicles (CAVs), and most researchers have studied the challenges and the opportunities related to them^{43,44}. The main aspect of switching towards the CAVs is the drivers' willingness to pay and use it⁴⁵. Thus, the research is needed to set the optimum toll rates based on the drivers' willingness to pay and the percentage of mixed traffic of human-driven vehicles and CAVs⁴⁶. Moreover, the effect on various traffic operations, such as lane preference to the CAVs, toll rates, lane choice mechanism for CAVS, etc. with an increase in CAVS penetration requires more focus for future studies^{47,48}.

Contribution of the present study

The study deals with the traffic operation at toll plazas with a comprehensive literature review. Capacity and level of service parameters have been focused on in the manuscript. The traffic operation in developing countries is entirely different from that in developed countries on any facility. The parameters related to capacities like service headway and LOS like the total delay are different in different traffic operations. In this context, there is a minimal study on traffic operation at toll plazas in developing countries like India. It has been found (Figure 1) that in the recent past, there have been several studies from India, and therefore this topic has been of keen interest for researchers in India in recent times. There are very few studies on equivalency factors, pair-wise vehicle leader-follower vehicle and their behaviour, etc. that can be taken up by the researchers in future, availing the benefits from the current study. Also, the researchers may focus on the research gap provided in the current study for future studies.

As far as the applicability part is concerned, the capacity is measured in veh/h considering the constant service headway for any vehicle class⁴. The same has been used in the design of toll plazas. The present work suggests that it varies with leader-follower class and within the same vehicle class; researchers have therefore proposed the equivalency factor. In order to operate the toll lane capacity in equivalent vehicle class/h will give better insight to the concessionaire to operate the number of lanes for approaching traffic at a different time of the day. Also, the concessionaire may get the LOS operation in mixed traffic conditions, and the management may be able to take the appropriate decision to maintain the designated LOS class.

Thus, the comprehensive review presented in this study is useful for the researchers and gives operational insight to the field engineers/concessionaires.

Conclusions

The present article presents a comprehensive review of the operational parameters of the toll plazas under homogene-

ous and mixed traffic conditions. The authors have tried to focus on essential parameters such as capacity, level of service, and equivalency factors for detailed review and proposed research gaps for potential researchers, especially in the prospect of developing countries. An effort has been made to bring out the limitations of the studies and to open up new avenues of research in further studies. It is noted that most of the studies are carried out in homogeneous traffic conditions, and there is a need to work out the capacity estimation and LOS for mixed traffic conditions. Further, to deal with the mixed nature of traffic, more emphasis should be given to the development of volume and traffic composition-based equivalency factors. Further, to the application part, the researcher may focus more on developing the equivalency factors and presenting the capacity in terms of equivalent vehicle class. The LOS may also be linked with the field observed parameter like approach volume to give inferences to the field engineers/concessionaires to maintain the desired LOS. Attempting such studies by potential researchers will provide meaningful insight into the societal contribution.

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