Bitlis Eren Üniversitesi Fen Bilimleri Dergisi
BİTLİS EREN UNIVERSITY JOURNAL OF SCIENCE
ISSN: 2147-3129/e-ISSN: 2147-3188
VOLUME: 12 NO: 3 PAGE: 797-807 YEAR: 2023
DOI:10.17798/bitlisfen.1311415

Enhancing Motorway Exit Efficiency: Determining the Ideal Number of Toll Booths

Göker AKSOY[1*]

[1] *Gebze Technical University, Institution of Transportation Technologies, 41400 Gebze, Kocaeli, Türkiye*
(ORCID: 0000-0003-4592-7048)

Keywords: Toll booth, Barrier control, Electronic toll collection, Manual toll collection, Service time.

Abstract

This study presents a model for determining the optimal number of toll booths at barrier-operated motorway exit toll booths in Istanbul, considering mixed traffic conditions and payment methods. In the past decade, Istanbul has experienced rapid growth in its road network due to public-private partnership (PPP) projects. However, despite relatively modest demand, long queues are frequently observed at the exit toll booths of newly constructed PPP motorways, which utilize barrier-controlled toll collection systems. These toll booths offer both electronic toll collection (ETC) and manual toll collection (MTC) options, with MTC users required to come to a complete stop for transactions, while ETC users experience reduced speeds. The presence of mixed payment methods leads to significant interactions between vehicles, resulting in longer service times and limited toll booth capacity. To evaluate the system, service times were measured considering four vehicle classes, payment methods of both the leading and serving vehicles, and whether the serving vehicle needed to wait for money exchange. The findings reveal that based on the current vehicle composition and considering only the utilization of the ETC system, 1.77 toll booths would be required to serve a demand of 1,800 veh/h/lane.

1. Introduction

Istanbul, as a megacity, faces challenges in terms of population growth and land use. To address the increasing demand for transportation, the public-private partnership (PPP) model has been implemented over the past decade, leading to significant transportation projects aimed at expanding the capacity of Istanbul's road network. However, the adoption of high-fee toll roads has not been fully realized. This limited adoption, along with a low user choice ratio, has resulted in constrained demand for the PPP motorway network in Istanbul.

In the context of PPP projects, private organizations initially finance road construction and subsequently charge tolls to recover their costs. To maximize revenue or prevent toll loss, barrier-controlled toll booths with both electronic toll collection (ETC) and manual (cash) toll collection (MTC) systems have been implemented. However, government-operated motorways utilize open tolling systems. In instances where drivers do not possess an ETC system, each exit toll booth is manned by a toll collector. Consequently, the number of operating toll booths fluctuates throughout the day due to the need for toll collectors with the MTC system. As a result, all types of vehicles utilize practically every toll gate, leading to a mixed use of toll booths by vehicles of varying sizes that employ either the MTC or ETC system. Despite the allocation of rightmost toll gates for heavy vehicles, regular cars frequently utilize these toll booths to bypass long queues.

The barrier-controlled exit motorway toll booths pose a significant bottleneck due to factors such as mixed payment options, mixed vehicle usage, and insufficient active toll booths. This leads to

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[*] Corresponding author: *gaksoy@gtu.edu.tr*

Received: 08.06.2023, Accepted: 19.09.2023

extended delays for users. In general, the low demand for PPP motorways results in minimal or negligible congestion issues, despite the long service times at toll booths. However, during peak travel periods such as the start or end of long public holidays, incidents, road closures, or congestion on alternative routes can cause a surge in demand. This leads to long queues and increased service times, even when all dedicated toll booths are operational. Additionally, the rerouting of heavy-load vehicle traffic to the newly constructed PPP motorways contributes to longer service times for specific vehicle classes. This indicates the need for a reevaluation of the required number of toll booths. Typically, in the PPP motorways of Istanbul, the number of barrier-operated toll booths used to be 2-2.5 times the number of available lanes. For instance, a four-lane motorway would typically have ten toll booths on both the entrance and exit sides. However, this number of toll booths is clearly inadequate for a four-lane motorway with the characteristics mentioned above. Additionally, it is observed that entrance toll booths have statistically shorter service times [1], yet the same number of toll booths have been installed on Istanbul's PPP motorways. Service times are influenced by various external factors, and it is necessary to reconsider either the physical design or the number of toll booths. The objective of this paper is to evaluate the required number of toll booths from this perspective.

In this study, the service times at barrier-operated exit motorway toll booths were measured, and the required number of toll booths was determined by considering various external factors. Given that service times at entry toll booths are significantly shorter [1], this study focuses exclusively on exit toll booths. The service time refers to the duration during which drivers spend paying the toll fee. Technically, the ETC system should have no service time. However, regardless of the payment method, each vehicle needs to decelerate and pass through a physical toll gate equipped with a barrier. Even for ETC payers, a small amount of time is required for electronic payment, transaction procedures, and barrier opening. Thus, service time does exist in the real world, although it is minimal. Consequently, service time measurements were conducted at exit motorway toll booths, considering four different vehicle classes, leader (the vehicle in the front of a line) and serving vehicle (the vehicle at the toll both) payment methods, and whether the serving vehicle needed to exchange money.

Motorway toll booths play a crucial role in ensuring uninterrupted traffic flow for drivers. However, if they are inadequately designed, they can become bottlenecks leading to significant delays and reduced travel comfort. One major contributing factor to bottlenecks in toll booth areas is the lane discontinuity between upstream and downstream directions. The service time, which directly affects capacity and service efficiency, is a critical factor in toll booth operations. Barrier-operated toll booths further exacerbate the situation, intensifying the bottleneck effect [2]. Service times at toll booths vary depending on vehicle class and payment method [3]. Increasing the usage of ETC systems has been shown to decrease queue lengths and delays, thereby improving overall efficiency [4]. Numerous studies have demonstrated the negative impact of barrier-operated toll booths on road safety [5-7] and air pollution [8].

Many researchers have previously covered motorway toll booths from various perspectives. One notable finding is that service times at barrier-controlled toll booths tend to be significantly longer compared to those without barrier control [2]. Additionally, Abdelwahab [9] determined that to alleviate excessive delays, the optimal number of toll booths should range from 14 to 18 when cash payment is used by 50 percent or more of the vehicles, and the hourly demand reaches 4000 vehicles per hour for barrier-controlled toll booths. These studies highlight the importance of considering factors such as payment methods and demand levels when determining the appropriate number of toll booths to ensure efficient traffic flow and minimize delays.

Previous studies have extensively examined various aspects related to toll payment systems, vehicle classes, delays, and queues in the literature. Bari et al. [10] focused on mixed traffic conditions and utilized seven different vehicle classifications to determine the delay experienced by vehicles using the MTC system and queue waiting time found between 5.06 sec to 298.04 sec. Al-Deek [11] found that the exclusive use of the ETC system reduced service times by 5 seconds compared to MTC. Aksoy et al. [12], through a microsimulation study, demonstrated a direct correlation between the number of toll booths and delays. Aycin et al. [13] evaluated the capacity of toll booths with mixed payment options by considering successive pairings of payment types for vehicles, such as MTC-MTC, ETC-MTC, ETC-ETC, and MTC-ETC. Similarly, Bari et al. [14] analyzed the service times of the MTC system in mixed traffic scenarios, considering factors such as follower-leader pairs, vehicle type, and toll rates. Lima et al. [15] found that payment method and the sex of toll booth workers had the most significant influence on service times in the MTC system, along with vehicle type. Navandar et al. [3] developed a methodology for estimating service times in mixed traffic conditions for seven different vehicle classes, highlighting that as the number of small-sized vehicles in the traffic stream increases, the service time decreases for those vehicles but increases for larger-sized vehicles. Deshmukh et al. [16] investigated service times for MTC systems in mixed traffic scenarios, considering seven distinct vehicle classes.

The comprehensive review of the literature highlights the significance of toll booth areas in terms of service time and capacity considerations, and various external factors. The payment method chosen by users and the presence of a barrier control system have a notable impact on service times. Similarly, user experiences are greatly influenced by increased delays and waiting times in queues. Moreover, the type of vehicle plays a crucial role in determining service times, which directly affects toll booth capacity. Additionally, the payment system and sequential pairings of vehicle payment methods also contribute to the overall operating conditions. The determination of the required number of toll booths was accomplished through the development of a service time estimation model, which took into account four distinct vehicle classes, the payment method of the leading vehicle, the payment method of the serving vehicle, and whether the serving vehicle needed to wait for money exchange (in the case of the MTC system). These data were collected from Istanbul's PPP highways, providing valuable insights for this study.

2. Material and Method

Service times were determined by analyzing video recordings of each payment transaction at the barrier operated Alemdag toll booth which is a part of Istanbul's PPP motorway. A total of 3,264 individual measurements were collected at this toll booth, covering various periods including weekdays and weekends. It is important to note that the data set excluded measurements taken during adverse weather conditions, focusing solely on bright days.

In this study, service time specifically refers to the time required to complete the toll payment transaction at the toll booth. Other factors such as queue waiting times and overall time spent on toll payment are influenced by arrival rates and various external variables. However, for the purpose of this study, the focus is solely on the time spent on the fee transaction itself, regardless of the queue length. The aim is to estimate service times based on the collected external parameters. The observed motorway segment includes four vehicle classifications, as given in Table 1: car (C), medium goods vehicle (MGV), truck & bus (TB), and articulated trucks (AT), with proportions of 70.82 percent, 11.85 percent, 8.24 percent, and 9.09 percent, respectively, out of the total 3,264 observations. ETC payment accounted for 86.73 percent of the transactions, while MTC accounted for the remaining 13.27 percent.

Table 1. Vehicle categories with their specifications.

Vehicle Class	Detail
1: Car (C)	Passenger car, pick-up, jeep, vehicles with up to 4-8 passenger capacity
2: Medium Goods Vehicle (MGV)	Vehicles with 8-25 person passenger capacity and trucks with 3.5 - 5 tonnes in weight
3: Truck & Bus (TB)	Vehicles with high load & passenger transport capability, 8-12 m in length.
4: Articulated Truck (AT)	Higher load capability with 10-18 m in length.

Service times at toll booths are influenced by multiple factors, including the payment amount, toll booth employee experience, payment method, and vehicle type [4]. Notably, there are significant variations in service times between cars and trucks [2]. However, it is worth noting that the literature lacks a standardized definition or implementation of service times. Mahdi et al. [1] measured service times at MTC toll booths as the duration between a vehicle's stop and start while considering ETC transactions to have a service time of zero in their microsimulation study. In contrast, Karim et al. [4] defined MTC service time as the time interval between a vehicle's stop and passing over a barrier. Interestingly, Karim et al. [4] assigned a service time of 5 seconds for ETC transactions. On the other hand, Lima et al. [15] defined MTC service times as the time interval between the start of a transaction and the complete departure of a vehicle. These variations in defining service times highlight the need for a standardized approach in toll booth studies.

Navandar et al. [3] provided a unique definition of service time, considering it as the sum of transaction time and travel time required to cover the vehicle's distance. Building upon this definition, the current study measured MTC service times from the moment the vehicle stops for a transaction until it completely passes the barrier. As for ETC payments, which do not require vehicles to stop during the fee transaction, service times were determined based on the time taken by vehicles to travel their distance within the payment section. It is important to note that even for ETC customers, service times can be affected by factors such as the delayed opening of a barrier and the long and narrow physical toll booth section. These conditions can result in reduced vehicle speeds and, in some cases, significantly increased ETC service times.

2.1. Descriptive analysis of the data

The measured service times in this study were categorized into eight groups, considering the combination of four different vehicle classes and two payment alternatives, as shown in Table 2. It is observed that MTC service times exhibit a higher level of dispersion, as evidenced by the larger standard deviation of MTC service times. Each group has its distinct pattern, and the coefficient of variation (CV) can be used to assess the spread of the data. The CV for the ETC system ranges between 20.6 and 23.8 percent, while for the MTC system, it ranges between 39.9 and 57.2 percent. Initially, the MTC system appears to have a higher level of variability compared to the ETC system.

Table 2. Descriptive statistics for the service times.

Vehicle Class	Sample Size	Minimum (sec)	Maximum (sec)	Mean	Std. Dev	CV
C - ETC	2051	1.1	5.2	2.42	0.574	0.238
MGV - ETC	336	1.9	6.8	3.27	0.763	0.233
TB - ETC	213	3.0	9.4	4.95	1.077	0.218
AT - ETC	231	4.6	13.3	8.14	1.675	0.206
C - MTC	261	6.1	58.2	22.07	12.638	0.572
MGV - MTC	51	8.3	50.0	21.89	12.372	0.565
TB - MTC	55	10.3	57.0	27.84	11.814	0.424
AT - MTC	66	10.5	66.0	35.66	14.224	0.399

Service times were further analyzed by considering various scenarios experienced by drivers, which go beyond the scope of vehicle classes and payment type combinations. By disregarding vehicle classes, eight distinct main scenarios were identified based on the payment method of both the serving and leader vehicles, as well as whether the serving vehicle waits for money exchange or not. Consequently, three scenarios were observed for ETC payments (E1 to E3), and five scenarios were observed for MTC payments (M1 to M5), as indicated in Table 3.

Table 3. Observed cases from the field.

Case No	Condition	Number of Occurrence	Occurrence Percentage
Case E1	ETC payment. No leader vehicle.	1,925	58.98
Case E2	ETC payment. Leader vehicle makes ETC payments too.	671	20.56
Case E3	ETC payment. Leader vehicle makes MTC payment.	235	7.20
Case M1	MTC payment. No leader vehicle. No money exchange.	384	11.76
Case M2	MTC payment. Leader vehicle makes ETC payment. No money exchange.	12	0.37
Case M3	MTC payment. Leader vehicle makes MTC payments too. No money exchange.	5	0.15
Case M4	MTC payment. Leader vehicle makes ETC payment. Waiting for money exchange.	19	0.58
Case M5	MTC payment. Leader vehicle makes MTC payments too. Waiting for money exchange.	13	0.40
Total		3,264	100.00

During the field observations, a total of eight different cases were recorded, each varying in terms of their occurrence frequency. The most common case, observed frequently, is Case E1, which involves

ETC payments by the serving vehicle without the presence of a leader vehicle. This can be attributed to the widespread adoption of the ETC system. As mentioned earlier, the low demand for PPP motorways contributes to the prevalence of Case E1. Cases E2 and E3, on the other hand, involve the presence of a leader vehicle, either with ETC or MTC payments, and were observed 671 and 235 times, respectively. These cases are relatively less common compared to Case E1.

The MTC system exhibits clear discrimination in terms of service times and toll booth capacity, particularly when the serving vehicle needs to wait for money exchange. Among the observed cases for the MTC system, there are a total of five subcases, with Case M3 being the least common. This implies that instances, where two successive MTC payments are made without waiting for money exchange, are rarely encountered. On the other hand, there are 32 observations in the dataset where vehicles had to wait for money exchange, which can lead to increased service times (Cases M4 and M5). Similar to the ETC cases, the majority of observations fall under Case M1, indicating that 384 separate MTC payments were made by vehicles without the presence of a leader vehicle at the toll booth. This highlights the prevalence of such scenarios within the MTC system.

3. Results and Discussion

To estimate the service time of a single toll booth, a multiple linear regression model is constructed. The model incorporates independent variables such as vehicle class, serving, and leader vehicle payment method, and whether the serving vehicle waits for money exchange. The service time is considered the dependent variable in this model. Since the independent variables are categorical, they are encoded as dummy variables. To determine the coefficients of the model, appropriate reference categories are carefully selected. In this case, AT is chosen as the reference category for vehicle classes, MTC is selected as the reference for both the serving and leader vehicle payment methods, and not waiting for money exchange is chosen as the reference for the money exchange variable. The estimated linear regression model with its calculated parameters can be found in Table 4.

Table 4. Calculated model coefficients with their statistics.

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.	95% Confidence Interval for B		Collinearity Statistics	
	B	Std. Error	Beta			Lower Bound	Upper Bound	Tolerance	VIF
(Constant)	19.216	0.479	-	40.098	0.000	18.276	20.155	-	-
Car (C)	-6.463	0.241	-0.325	-26.780	0.000	-6.937	-5.990	0.381	2.627
MGV (MGV)	-5.604	0.301	-0.201	-18.637	0.000	-6.194	-5.015	0.485	2.063
Truck & Bus (TB)	-3.925	0.326	-0.119	-12.035	0.000	-4.565	-3.286	0.571	1.751
Payment Method (PM)	-9.481	0.346	-0.356	-27.417	0.000	-10.159	-8.803	0.333	3.004
Leader Payment None (LPNo)	-1.059	0.257	-0.053	-4.121	0.000	-1.563	-0.555	0.335	2.986
Leader Payment ETC (LPETC)	-0.826	0.284	-0.038	-2.910	0.004	-1.382	-0.269	0.337	2.968
Money Exchange (ME)	16.821	0.406	0.539	41.431	0.000	16.025	17.617	0.332	3.012

Before discussing the model outcomes, the dummy variables in Table 1 have to be clarified. As mentioned earlier, AT is chosen as the reference category for vehicle classes. Therefore, in the regression model, the C, MGV, and TB variables should be zero to represent the selection of the reference category. For the payment method (PM) variable, MTC is selected as the reference category. There are three different alternatives for the leader payment (LP) variable: MTC, ETC (LPETC), and the absence of a leader vehicle (LPNo). Since the reference category is set to MTC, LPNo will take a value of 1 in the absence of a leader vehicle, LPETC will take a value of 1 when the leader pays with ETC, and both LP coefficients will be zero when the leader pays with MTC. Similarly, for the money exchange (ME) variable, it should be 1 if a serving vehicle is waiting for a money exchange, as indicated by the positive and high coefficient value of ME. Finally, the service time estimation model is derived using multiple linear regression, as shown in Equation 1.

$$\boldsymbol{ST} = 19.216 + [-6.463 \times C - 5.604 \times MGV - 3.925 \times TB] + [-9.481 \times PM] + [-1.059 \times LPNo - 0.826 \times LPETC] + [16.821 \times ME] \quad (1)$$

In Equation 1, the constant is calculated as 19.216 seconds, and ST represents the service time in seconds. The signs of each coefficient in the regression model should be carefully analyzed. The negative signs for the C, MGV, and TB coefficients indicate that the reference category, AT, has a negative influence on service times. This means that if any of these dummy variables is one, the corresponding vehicle class will have a shorter service time compared to the reference category. Consequently, the reference category (AT) will have the highest service time. When comparing the dummy variables with one another, the C coefficient has the greatest reduction influence on service time compared to TB and MGV, while MGV is placed between them. This suggests that as the vehicle size increases, the service time also increases, regardless of the other parameters included in Equation 1. This finding is further supported by the standardized coefficients column, which represents the relative effect of each variable compared to the others.

The negative sign of the PM coefficient in Equation 1 indicates that MTC has a comparable disadvantage in terms of service times. Since the reference category is MTC, a value of one for PM implies that ETC payment is chosen, resulting in a reduction of service time by 9.481 seconds. In other words, regardless of the other parameters considered in the model, using the ETC system alone leads to a reduction in service time by 9.481 seconds compared to the MTC system.

The negative signs of the LPNo and LPETC dummy variables in Equation 1 demonstrate the disadvantage of the reference category. The presence of a leader vehicle with MTC payment significantly increases service times. On the other hand, when the leader vehicle pays with ETC, it slightly increases service time compared to the absence of a leader vehicle (1.059 > 0.826). Although the difference is relatively small, in real-world situations, service time will likely be lower when there is no leader vehicle ahead of the approaching vehicle. This observation is consistent with the results obtained from the regression model.

Since the reference category is selected as "no waiting for money exchange," the ME dummy variable has the highest and positive coefficient in Equation 1. This indicates that anticipating money exchange will increase the service time of a vehicle. The positive sign of the ME coefficient implies that, when all other factors are ignored, the variable alone increases the service time by 16.821 seconds. This finding highlights the significant impact of waiting for money exchange on overall service times.

Table 4 demonstrates that the model coefficients for all parameters are statistically significant, as indicated by the p-values (<0.05) associated with each independent variable. The tolerance values, which indicate the amount of variability shown by a specific independent variable in the model's collinearity statistics, were all found to be greater than 0.1. A smaller tolerance value would suggest redundancy among variables, but in the estimated model, all tolerance values are greater than 0.1, indicating that each independent variable contributes unique information to the model and that the variance in the dependent variable cannot be fully explained by the other independent variables. Additionally, the variance inflation factor (VIF) values were found to be less than 5, which is generally preferred to avoid issues of multicollinearity. Table 5 provides a summary of the model, presenting these findings.

Table 5. Model summary of service time estimation.

R	R Square	Adjusted R Square	Std. Error of the Estimate	Durbin-Watson
0.904	0.817	0.817	3.867	2.033

Table 5 presents an evaluation of the model's goodness of fit. The R-squared value, which indicates the proportion of variance in the dependent variable explained by the independent variables, is determined to be 81.7 percent. This means that 81.7 percent of the variability in the dependent variable (service times) can be accounted for by the independent variables included in the model. Consequently, it can be concluded that the constructed model is effective in estimating service times based on the selected independent variables.

3.1. Determination of the number of toll booths

The estimated model considers various external factors, including vehicle class, to estimate service times at a single toll booth. Based on Equation 1, service times can be calculated, allowing for the evaluation of the number of toll booths needed under different conditions. To assess this, service times were computed using Equation 1 for the observed cases listed in Table 3. The resulting service times are presented in Figure 1.

For each vehicle class, the shortest estimated service times were determined for cases E1, E2, and E3. The minimum service time for vehicle class C in case E1 is calculated to be 2.21 seconds. However, Figure 1 demonstrates that even when the ETC system is utilized, the vehicle class AT requires a considerably longer service time of 8.67 to 9.73 seconds for cases E1, E2, and E3. These extended service times undoubtedly lead to significant queues and congestion.

Figure 1 illustrates the impact of waiting for money exchange in cases M4 and M5. Interestingly, there are negligible differences between vehicle classes in terms of money exchange anticipation. The shortest calculated service time for these cases is 28.75 seconds for vehicle class C in case M4, while the highest is 36.04 seconds for vehicle class AT in case M5. On the other hand, due to the absence of waiting for money exchange, the service times for cases M1, M2, and M3 are lower compared to cases M4 and M5. Both Figure 1 and Equation 1 demonstrate the influence of vehicle size, waiting for money exchange, and other previously mentioned parameters on service times.

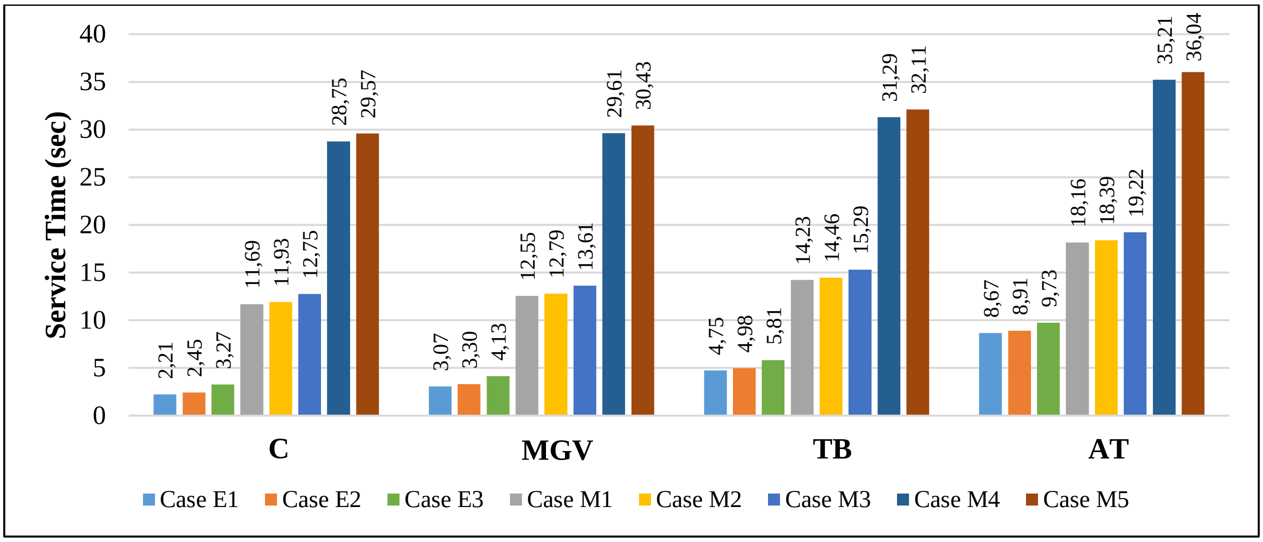

Figure 1. Service time estimates for observed cases.

Indeed, the prevalence of scenarios M1 through M5 at a toll booth will undoubtedly result in longer service times and the need for additional toll booths. Conversely, if the traffic flow primarily consists of cases E1 through E3, a lower number of toll booths might be sufficient. Additionally, vehicle class has a significant impact on service time, with larger-sized vehicles experiencing longer service times. Moreover, the overall volume of traffic on a motorway is a crucial factor in determining the appropriate number of toll booths required. In summary, the vehicle class, occurrence of the eight cases, and the volume of traffic all play a vital role in determining the necessary number of toll booths and managing motorway congestion effectively.

Table 3 presents the frequencies of cases observed during service time measurements, while Table 2 provides the distribution of vehicles across different classes. In this section, Equation 1 has been utilized to investigate the trends in MTC usage and changes in vehicle composition. Consequently, the number of required toll booths was estimated. It was found that only 13.27 percent of vehicles in the observed dataset used MTC, with the remaining composition consisting of 70.83 percent for class C, 11.86 percent for MGV, 8.21 percent for TB, and 9.10 percent for AT. These percentages reflect the proportions of each vehicle class within the dataset.

The computation methodology presented in Table 6 was utilized to calculate the number of toll booths needed. The vehicle arrivals were assumed to be deterministic, without any external stochastic influences. The total required service time was determined based on this assumption, and the number of toll booths required was obtained by dividing the total required service time by 3,600. Table 6 provides an illustrative example scenario, including the observed volume and the existing vehicle composition, to demonstrate the application of the methodology.

Table 6. Calculation procedure.

Cases			X: Volume considering total volume (veh/h)				Y: Service time for dedicated cases (sec)				X*Y: Total required service duration (sec)				# toll booth
No	**#**	**%**	**C**	**MGV**	**TB**	**AT**	**C**	**MGV**	**TB**	**AT**	**C**	**MGV**	**TB**	**AT**	
E1	1925	58.98	1363.5	228.2	158.1	175.2	2.21	3.07	4.75	8.67	3015	701	751	1520	4.23
E2	671	20.56	475.3	79.6	55.1	61.1	2.45	3.30	4.98	8.91	1162	263	275	544	
E3	235	7.20	166.5	27.9	19.3	21.4	3.27	4.13	5.81	9.73	544	115	112	208	
M1	384	11.76	272.0	45.5	31.5	34.9	11.69	12.55	14.23	18.16	3180	571	449	634	
M2	12	0.37	8.5	1.4	1.0	1.1	11.93	12.79	14.46	18.39	101	18	14	20	
M3	5	0.15	3.5	0.6	0.4	0.5	12.75	13.61	15.29	19.22	45	8	6	9	
M4	19	0.58	13.5	2.3	1.6	1.7	28.75	29.61	31.29	35.21	387	67	49	61	
M5	13	0.40	9.2	1.5	1.1	1.2	29.57	30.43	32.11	36.04	272	47	34	43	
Total	3264	100	2312	387	268	297	-	-	-	-	8708	1790	1690	3038	-
Grand Total	-	-	3264				-	-	-	-	15226				-

To explain the calculation method, consider a total of 3,264 vehicles observed, consisting of 2,312 vehicles in class C, 387 in MGV, 268 in TB, and 297 in AT. It can be assumed that these numbers represent the hourly volume of the toll booth area, along with the observed case occurrences and percentages for each vehicle class. The "Volume" column (X) in Table 6 is computed by multiplying the case percentages with the total hourly volume of 3,264 vehicles. The "Service times for dedicated cases" column (Y) is derived using Equation 1, as shown in Figure 1. The total required service duration (X*Y) is obtained by multiplying the service times by the volume counts for each case and vehicle type. Consequently, the total required service duration is computed for each vehicle class and case. The overall necessary service duration for the provided hourly volume and case percentages is calculated as 15,226 seconds, with 8,708 seconds for class C, 1,790 seconds for MGV, 1,690 seconds for TB, and 3,038 seconds for AT. This means that if the vehicles arrive at the toll booth deterministically over an hour, 15,226/3,600 = 4.23 toll booths would be required for the 3,264 vehicles.

The same computation approach is employed to analyze different vehicle compositions and MTC payment percentages. This allows us to examine and explain the impact of both vehicle classes and the MTC system. Table 7 shows the number of toll booths required for a volume of 1,800 vehicles per hour, considering various vehicle compositions and the percentage of MTC system usage.

Table 7. Required number of toll booths for different vehicle compositions.

Volume (veh/h/lane)	MTC percent	Vehicle composition (percent for vehicle class 1 to 4)					
		Existing	**64-12-12-12**	**55-15-15-15**	**46-18-18-18**	**40-20-20-20**	**25-25-25-25**
1,800	0	1.77	1.91	2.06	2.21	2.31	2.55
	25	3.81	3.95	4.10	4.25	4.34	4.59
	50	5.84	5.99	6.13	6.28	6.38	6.63
	75	7.88	8.02	8.17	8.32	8.42	8.66
	100	9.92	10.06	10.21	10.36	10.46	10.70

In Table 7, the distribution of cases (E1 to M5) is assumed to be equal, unlike the observed case percentages in Table 3. This allows for a more straightforward evaluation of the effects of the MTC system and changes in vehicle composition. For the existing vehicle composition (70.83 percent C, 11.86 percent MGV, 8.21 percent TB, and 9.10 percent AT), it would require 1.77 toll booths if all drivers used ETC (600 vehicles for case E1, 600 for case E2, and 600 for case E3). However, if 100 percent of vehicles (360 vehicles for case M1, 360 for case M2, 360 for case M3, 360 for case M4, and 360 for case M5) used the MTC system, 9.92 toll booths would be needed. The transition from 0 percent to 100 percent MTC usage is quite significant, but the impact on vehicle compositions is less pronounced. The first group, composed of 64 percent C, 12 percent MGV, 12 percent TB, and 12 percent AT, would require between 1.91 and 10.06 toll booths. The latter group, with equal distribution of vehicles (25 percent each), would require between 2.55 and 10.70 toll booths.

Toll booth capacity needs to be evaluated considering both changes in vehicle composition and the percentage of MTC usage. Therefore Figure 2 is generated by dividing the volume by the required number of toll booths from Table 7. When there is zero percent MTC usage and the existing vehicle composition is considered, the highest toll booth capacity is calculated as 1017 veh/h/lane. However, even if all drivers use the ETC system and vehicle composition is equally distributed among all vehicle classes (25 percent each), toll booth capacity decreases by approximately 30 percent from 1017 to 705 veh/h/lane. As the MTC usage percentage increases, toll booth capacities decrease, and the disparities in vehicle composition become almost negligible. When 100 percent of drivers prefer the MTC system, toll booth capacity is calculated as 181 veh/h/lane for the existing vehicle composition, and it decreases by 7 percent to 168 veh/h/lane for equally distributed (25 percent each) vehicle composition. As MTC usage grows, the differences between vehicle classes diminish significantly.

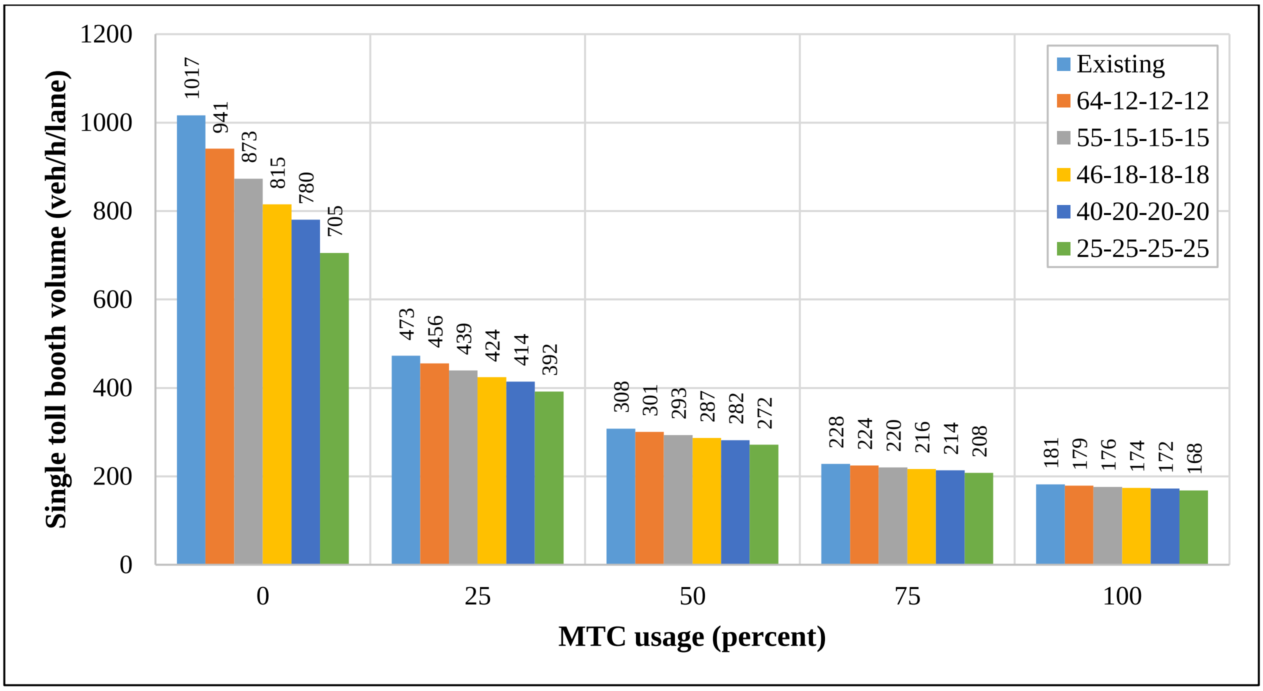

Figure 2. Single toll booth capacities.

Furthermore, the MTC system has a more significant impact on service times (and capacities) compared to changes in vehicle composition. In any scenario, toll booth capacity experiences a substantial decrease, highlighting the inefficiency of the MTC system. However, it is important to note that this model estimates service times for barrier operated toll booths. Even if 100 percent of drivers use the ETC system, at least two toll booths per lane are required for the existing composition because the capacity is lower than the demand (1,800>1,017 veh/h). Additionally, a significant impact on system performance is observed with only 25 percent MTC usage. When 25 percent of MTC is in use, toll booth capacity decreases from 1,017 veh/h/lane to 473 veh/h/lane for the existing vehicle composition, representing a 54 percent capacity loss. Capacity losses for the 50, 75, and 100 percent MTC usage conditions are computed as 70, 78, and 82 percent, respectively, for the existing traffic composition.

4. Conclusion and Suggestions

Motorways offer a seamless and convenient travel experience in exchange for toll fees. Various payment methods are available and widely accepted by motorway users. Advancements in technology have significantly reduced the time required for fee transactions. Electronic payment options enable fast and efficient transactions, eliminating the need for time-consuming cash transactions.

Cash (MTC), near field communications, and radio frequency identification (RFID) technologies are commonly used toll payment methods on motorways. While all these methods serve the purpose of toll collection, the emphasis is on ensuring uninterrupted traffic flow during the payment process. Although the MTC system is considered outdated for state motorways, it still holds its appeal for fee collection on barrier-controlled public-private partnership (PPP) motorways, primarily due to financial considerations. In mixed traffic scenarios, where both ETC and MTC systems are in use, all vehicles must pass through the same toll booths. This can lead to driver inconvenience and confusion, as they need to make a decision on which toll gate to approach. Moreover, when combined with the presence of a leading vehicle using the MTC system, the complexity and difficulties are further amplified. Therefore, it is important to have a well-designed system in place that considers the required number of toll booths to minimize delays, and queues, and improve the overall level of service.

This article proposes a toll booth calculation model that considers various external variables, including different vehicle classes, payment methods of both the leader vehicle and serving vehicle, and whether the serving vehicle waited for money exchange. The model is developed based on 3,264 field observations, allowing for the calculation of the required service time for each vehicle and the determination of toll booth capacity. By considering the payment method and other relevant external parameters, the model approximates the service time of each vehicle class accurately.

The model provides valuable insights into the service times for different vehicle classes and payment methods. For ETC users without a leader vehicle, cars (C) have a minimum service time of 2.21 seconds, while articulated trucks (AT) have a minimum service time of 8.67 seconds. Medium goods vehicles (MGV) and truck & bus (TB) classes have minimum service times of 3.07 seconds and 4.75 seconds, respectively. In the worst-case scenario, where a vehicle approaches an occupied toll booth, uses MTC as the payment method, and waits for money exchange, the estimated service times are 29.57 seconds for cars (C) and 36.04 seconds for articulated trucks (AT). It is evident that the service times are influenced by both the payment method chosen by the serving vehicle and the leader vehicle's preferred payment method, as well as whether the serving vehicle waits for money exchange. This results in eight distinct cases based on the combinations of leader and serving vehicle payment methods and money exchange anticipation. The best-case scenario for an approaching vehicle is to encounter a completely empty toll booth, while the worst-case scenario involves approaching an occupied toll booth as an MTC user, with MTC payment and the anticipation of money exchange.

Using the developed model, the impact of vehicle composition and variations in vehicle composition is examined. Based on the current vehicle composition (70.83 percent C, 11.86 percent MGV, 8.21 percent TB, and 9.10 percent AT) and considering only the utilization of the ETC system, it is estimated that 1.77 toll booths would be required to serve a demand of 1,800 veh/h/lane. However, this number increases to 2.55 toll booths when the vehicle composition is evenly distributed (25 percent each) across all vehicle classes. As the usage of the MTC system increases, the number of required toll booths also tends to increase. For the existing vehicle composition, if 100 percent of drivers prefer the MTC system, it is estimated that 9.92 toll booths would be required to serve the demand of 1,800 veh/h/lane.

The capacity of a toll booth is directly influenced by service times, which in turn are affected by the percentage of MTC usage and the vehicle composition. Both factors play a comparable role in determining capacity and service times. When all drivers prefer the ETC system, the calculated capacity of a single toll booth is 1017 veh/h/lane for the existing traffic composition. However, for an equally distributed vehicle composition (25 percent for each vehicle class), the capacity decreases to 705 veh/h/lane. In the case where all drivers prefer the MTC system, the toll booth capacities range from 168 to 181 veh/h/lane. Interestingly, even with only 25 percent of drivers using the MTC system, the mixed usage of toll booths by MTC, and ETC customers results in a significant reduction in capacity. For the existing traffic composition, the toll booth capacity decreases to 473 veh/h/lane from the initial 1017 veh/h/lane, representing a 54 percent capacity reduction.

The toll booth areas play a vital role in ensuring efficient and satisfactory journeys for drivers. It is crucial to accurately determine the number of toll booths and design them appropriately to meet the needs of the traffic flow. The study's findings indicate that even with 100 percent ETC usage, service times still exceed 2 seconds. This suggests that to handle the capacity effectively, a minimum of two toll booths per motorway lane is necessary for the C vehicle class alone. It is evident that the precise estimation of the required toll booth number is essential, taking into consideration the projected demand and vehicle composition. In this regard, the presented model provides a clear estimation of the necessary toll booths in such scenarios.

Future research in this field will focus on incorporating the stochastic nature of traffic flow into the analysis. Recognizing the impact of randomness on the overall system conditions, future efforts will aim to evaluate queue length while considering the stochastic characteristics of traffic flow and delays. Additionally, it will be important to develop estimation models for assessing the level of service in relation to the number of toll booths, taking into account the variability and unpredictability inherent in traffic patterns. By considering these factors, future studies can provide more comprehensive and accurate insights into toll booth operations and their impact on traffic flow.

Conflict of Interest Statement

On behalf of all authors, the corresponding author states that there is no conflict of interest.

Statement of Research and Publication Ethics

The study is complied with research and publication ethics.

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