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Examınatıon of Delay and Travel Tıme at Hıghway Toll Booths Usıng A Mıcro Sımulatıon Program: Example of Northern Marmara Hıghway Kurnaköy Toll Booth

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Abstract

The aim of this study is to reveal that barrier toll booths are inefficient in terms of delay and travel time when compared to non-barrier toll booths. In our study, Kurnaköy toll booth, on the Northern Marmara Highway, was examined. The toll booth was modeled using the PTV Vissim micro simulation program. Currently, 8 toll booths are in active service and are operated with barriers. As an alternative to the current operation, 4 different operations were modeled: 8 toll booths without barriers, 10 toll booths without barriers, 12 toll booths without barriers and finally 4 toll booths with free passage system. The designed models were run under 3 different demand levels as low, medium and high, and compared using the PTV Vissim program. When the current barrier toll booth and the non-barrier operations were compared with medium demand, it was seen that there is a significant difference in delay. A bottleneck problem was also encountered due to the geometry of the barrier-free toll booth operation. The optimum operation was found by comparing the alternative operations.

Keywords: Toll booth, delay, travel time, PTV Vissim, congestion

1. Introduction

Kurnaköy toll booth, which was examined within the scope of this study, is one of the toll booths on the Northern Marmara Highway. The toll booth was modeled using the PTV Vissim micro simulation program. The program was run for a total of 10.5 hours. The first half of this time was the warm-up time. Barrier and non-barrier operations were compared by modeling alternative operations to the current operation. According to the outputs from the program, the aim was to examine the effects of barrier toll booths on delay and travel time. In addition, the effect of the change in the number of toll booths on delay and travel time was examined.

Kurnaköy toll booth is operated with a barrier fee collection system. There are 2 types of fee collection: via electronic payment or payment by cash or credit card. The fee is calculated based on the difference between the entrance toll booth and exit toll booth. If the vehicles passing through the entrance toll booth have OGS (Automatic Pass System) or HGS (Fast Pass System), they approach the barrier and continue as the barrier opens. When they arrive at the exit toll booth, both those that have OGS or HGS approach the barrier in the same way, then the payment is taken electronically. However, vehicles that do not have OGS or HGS, stop at the entrance barrier, take a ticket from a ticket station and continue. When they arrive at the exit toll booth, they pay using cash or credit card. Due to the use of different payment methods, different service times occur at the entrance and exit toll booths. Service time can be defined as the time taken from when the vehicle approaches the toll booth and completes payment until it leaves. Service time can be affected by many factors. The first of these is the payment method. Due to the fact that money is exchanged at the cash payment toll booths, the service time is longer than toll booths that use electronic payment methods.

According to both Yavuz Sultan Selim Bridge and Northern Marmara Motorway Administration, one of the reasons for using barriers at entrance and exit toll booths is to ensure the controlled passage of vehicles making cash payments. Another reason is that vehicles with OGS or HGS are not affected if there is any problem in the transponder. However, there are some disadvantages to barrier toll booths. Studies have been carried out on the risk of accidents at toll booths. When the toll booths with barriers are compared with the toll booths with fully automatic passage, there are 72.6% fewer accidents in the toll booths with automatic passage compared to the toll booths with barriers [1]. According to the results of another study, a 42.1% decrease was observed in the overall accident occurrence with the removal of barrier toll booths [2]. In a further study, a 22% decrease was observed in the total accident rates after the toll booth without barrier design was implemented [3].

2. Literature Review

In the literature, many studies have been carried out for investigation and improvement of the operation of toll booth areas. Different micro simulation programs were used in these studies. In some studies, the toll booth was modeled using the PTV Vissim micro simulation program [4-6]. There are also studies modeled using the PARAMICS micro simulation program [7-8]. In one study, delay values decreased by 3% to 18% with the use of electronic toll collection instead of cash-operated toll booths [8]. The TPSIM micro simulation program has also been used to model the toll booth area [3,9]. In other studies, the toll booth area was analyzed using different simulation models [10-12]. By using queuing analysis and simulation models, the so-called hybrid model, together, an analysis of the toll booth area was carried out [13]. Manual calculation methods have also been used without using any simulation model [14]. In addition, there are toll booth studies modeled using the SHAKER micro simulation program [15] and ARENA micro simulation program [16]. A further study area carried out in the toll booth area is the bottleneck problem. Toll booth geometry can affect congestion. The number of lanes of the toll booth area can be higher than in the highway section to increase the capacity of the toll booth area, but if the number of lanes suddenly drops after the toll booth, then congestion occurs. This type of congestion is called bottleneck congestion. There are specific studies that deal with this problem. In one study, it was stated that congestion occurred in the section where the lanes decreased due to the excess capacity in the toll booth area [17]. Sahin [18] conducted a study on the toll booth at the Bosporus Bridge in Istanbul. He stated that toll booths can cause bottlenecks and that a bottleneck is one of the most important reasons for congestion.

In our study, delay values were used as performance criteria as other researchers have done [3,9,12], as they are more measurable and perceptible criteria than speed. Astarita [11] conducted a comparative study between cash and electronic toll booths. Capacity and delay values were taken into account as performance criteria. According to the results, the electronic payment system significantly increased capacity and reduced congestion. In the study of Klodzinski [3], the effects of the Free Pass System in the toll booth were examined. Delay values were used as the performance criteria. According to the results of the study, in the Free Pass System, delay was decreased by 49.8% compared to the cash payment method.

3. Materials and Methods

This study was conducted at the Kurnaköy tollbooth. A Google Earth view of the Kurnaköy toll booth is shown in Figure 1. Delay and travel time measurement points are also shown. Section A-A' represents the start and end points of the delay and travel time measurement points. The section length was set as 1070 meters and the delay and travel time of the vehicles were analyzed in that interval, at the exit toll booth in the A-A' direction.

Fig. 1. Study Area

The existing toll booth is operated as 6 lanes in the entry direction before the toll booth and 8 lanes at the exit in the A-A’ direction. The road leaving the toll booth has 4 lanes. The current toll booth design and alternative operations were analyzed in our study. A toll booth with 8 lanes without barrier operation was observed in order to analyze the effects of the barrier-free operation as an alternative to the current operation. As another alternative, a toll booth with 10 lanes was modeled as barrier-free. In order to observe the effect of an increase in the capacity of the toll booth, it was remodeled as 12 lanes. Finally, the toll booth with 4 lanes was modeled and analyzed. By using these operations, it was aimed to examine the effects of the barrier situation on delay and travel time. Another aim was to examine how the changes in the number of lanes affect delays in barrier-free operations. As the number of lanes increases, a possible delay due to a bottleneck is predicted. For this reason, analysis has been carried out on toll booths with different numbers of lanes.

3.1 Service Time

Service time is one of the most important parameters for the operation and evaluation of toll booths, and there are many variables that affect it [12]. Vehicle type and payment method are two important parameters [19]. Mahdi [20] used video recordings for service time for toll booths using cash payment method. It was measured as the time elapsed from the moment vehicles came to a complete stop to the moment they started their first onward movement. In the toll booths where payment was made electronically, the service time was taken as 0 seconds since the vehicles pass without stopping. Karim [16] measured service time as the time elapsed from the moment the vehicle stopped to the moment the vehicle passed the barrier. The service time of vehicles that pay electronically was taken as 5 seconds. In the study of Lima [21], service time was measured as the difference between the entry and exit times of vehicles to the toll booth area. Arrival time was defined as the moment when the vehicle came to a complete stop and departure time was defined as the moment when the vehicle left the barrier. For vehicles that paid without stopping, the time between the moment the payment starts and the moment the vehicle completely crosses the barrier was measured to determine service time. Navandar [19] measured service time as the summation of the time taken for the payment process and for the vehicle to travel the distance of its own length. In the study, video recordings were used for determination of the service time. In our study, service time was measured differently for vehicles using cash and electronic payment methods. For the cash payment method, the time from the moment the vehicle stops to pay until the vehicle leaves the barrier completely was measured as the service time. For the electronic payment method, since vehicles did not stop, service time was transferred to the program as 0 seconds.

PTV Vissim micro simulation program was used in this study. In this program, the barrier feature was added with the "Stop Sign" feature of the program. This function keeps the vehicles at that point according to the assigned service time values and allows the vehicles to pass after the service time has elapsed. When the studies carried out in the literature are examined, it is seen that there is a problem for vehicles that pass using the electronic payment method. In the current operation, it was observed that when vehicles using the electronic payment method approached the barriers, their speed significantly reduced, but most of the time they passed without stopping. In this case, even setting the service time value as 1 second to the simulation, is not compatible with reality. In our study, 4 different vehicle types were used (cars, trucks, buses and service vehicles). To solve the service time problem for electronic payment, two of each vehicle type were created. The vehicle type automobile was created for the cash payment method, while the vehicle type automobile-1 was created for electronic payment and the waiting time set to 0 seconds. Thus, more realistic results were obtained.

Service times were measured using video recordings for each vehicle type. Service times can be entered in PTV Vissim in two different ways. In the first way, they can be transferred to the model based on how long the vehicles will wait at the toll booths by entering the average and standard deviation of the measured service times. However, this option may cause longer waiting than the actual situation and so reduces the realism of the model. Therefore, the second option, the empirical distribution method, was used. The cumulative distribution of service times obtained from the video recordings was transferred to the program, and thus the closest situation to reality was modelled.

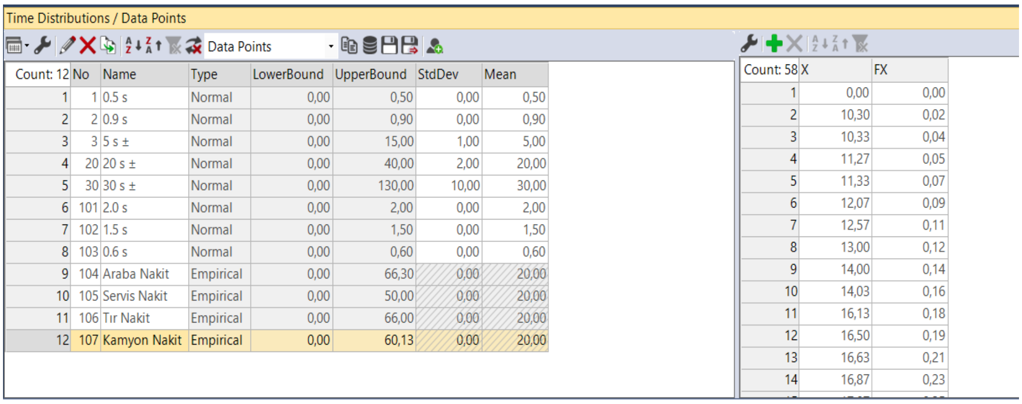
3.2 Vehicle Distribution

Another type of data transferred to the micro simulation program from the video recordings is vehicle distribution. The video recordings were examined at the exit toll booth. The results of these observations are shown in Table 1. Of the vehicles arriving at the toll booth, approximately 71% are automobiles, 9% are trucks, 9% are buses and 12% are service vehicles. The distribution of using cash payment method and electronic payment method is also shown in Table 1. In the default settings in the PTV Vissim program, three different vehicle types (car, truck and bus) are defined. However, according to the results obtained from the video recordings, it is seen that the rate of service vehicles cannot be ignored. In order to obtain better results, an additional type of vehicle was defined in the PTV Vissim program. Average service vehicle length and acceleration values were entered into the program and transferred to the model as a new vehicle type. The vehicle distribution obtained from the video recordings was transferred to the micro simulation program. Analysis of current and alternative operations was made according to this distribution, in order to obtain the closest results to the real situation.

Table 1.Vehicle distribution

Vehicle Type	Number	Percentages
1(Automobile)-Cash	263	8%
1-OGS/HGS	2062	63%
2(Service Vehicle)-Cash	51	2%
2-OGS/HGS	338	10%
3(Truck)-Cash	66	2%
3-OGS/HGS	231	7%
4(Bus)-Cash	57	2%
4-OGS/HGS	214	7%

One of the most important parameters in the designed model is the method of transferring the service time to the model. Two different time distributions are used in PTV Vissim. In this study, the empirical distribution was used for the service time. The distribution created from the data obtained from the video recordings was carried out in the window opened by following the "Base Data - Distribution - Time" tabs of Vissim. Vissim's default settings use time distribution with mean and standard deviation. A new time distribution was obtained for 4 different vehicle types by using the add tab for empirical distribution. The window in PTV Vissim is shown in Figure 2.



Time Distributions / Data Points

Data Points

Count: 12	No	Name	Type	LowerBound	UpperBound	StdDev	Mean
1	1	0.5 s	Normal	0,00	0,50	0,00	0,50
2	2	0.9 s	Normal	0,00	0,90	0,00	0,90
3	3	5 s ±	Normal	0,00	15,00	1,00	5,00
4	20	20 s ±	Normal	0,00	40,00	2,00	20,00
5	30	30 s ±	Normal	0,00	130,00	10,00	30,00
6	101	2.0 s	Normal	0,00	2,00	0,00	2,00
7	102	1.5 s	Normal	0,00	1,50	0,00	1,50
8	103	0.6 s	Normal	0,00	0,60	0,00	0,60
9	104	Araba Nakit	Empirical	0,00	66,30	0,00	20,00
10	105	Servis Nakit	Empirical	0,00	50,00	0,00	20,00
11	106	Tır Nakit	Empirical	0,00	66,00	0,00	20,00
12	107	Kamyon Nakit	Empirical	0,00	60,13	0,00	20,00

Count: 58	X	FX
1	0,00	0,00
2	10,30	0,02
3	10,33	0,04
4	11,27	0,05
5	11,33	0,07
6	12,07	0,09
7	12,57	0,11
8	13,00	0,12
9	14,00	0,14
10	14,03	0,16
11	16,13	0,18
12	16,50	0,19
13	16,63	0,21
14	16,87	0,23

Fig. 2. Empirical Distribution in PTV Vissim

While the service times obtained from the video recordings of the relevant vehicle type were entered on the X axis, the values obtained as a result of the cumulative distribution were entered on the FX axis. The service time distribution obtained for all four different vehicle types was obtained and is shown in Figure 3.

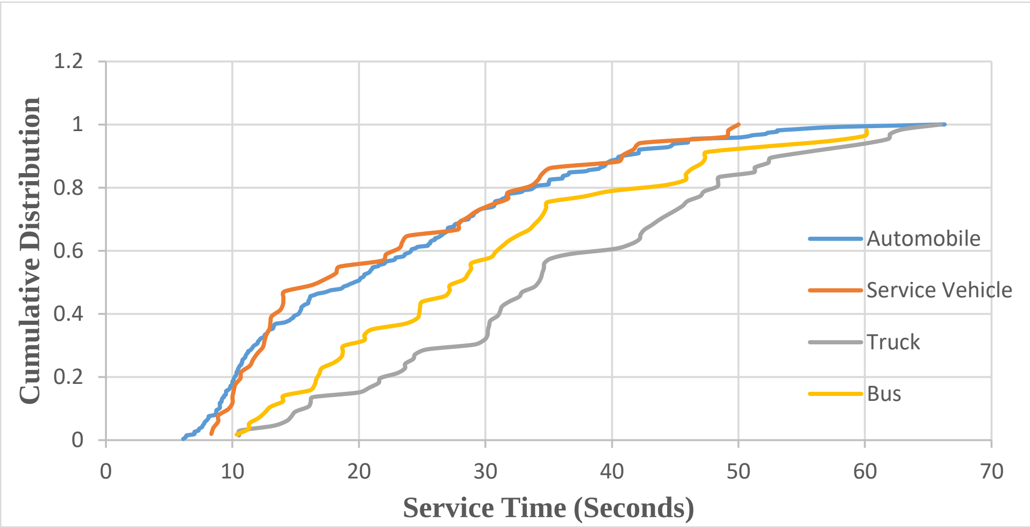


Fig. 3. Service Time

In this study, 5 different operations were compared: the current Kurnaköy toll booth and four differently-designed alternative operations. A summary of the designed operations is shown in Table 2 below.

Table 2. Summary of designed operation

	With Barrier	Barrier-free	#Toll Booth
Current Design	x		8
Alternative Design 1		x	8
Alternative Design 2		x	10
Alternative Design 3		x	12

Alternative Design 4		x	4

A demand curve was determined to compare the operations modeled. The modeled operations were loaded and run according to the demand curve created, then the outputs obtained from the program were compared. Three different demand curves were used in this study (Low-Medium-High). The purpose of using three different demand curves is to analyze the response of the toll booth to change in demand. The demand curves are shown in Figure 4 below.

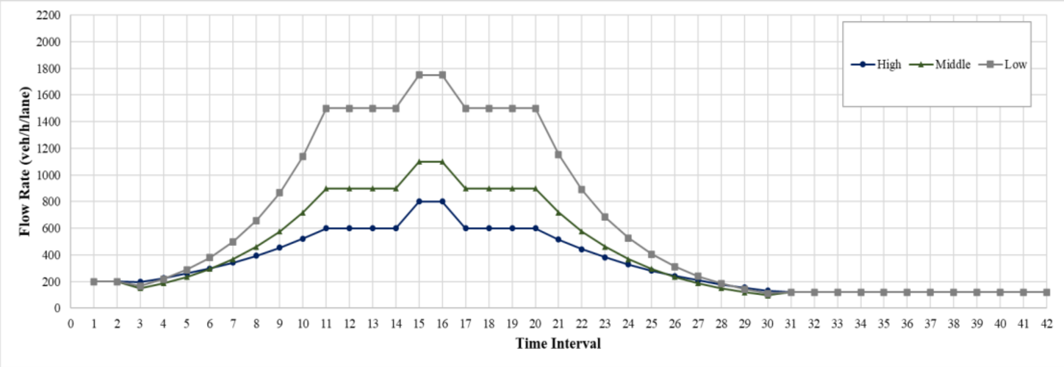


Fig. 4. Demand Curve

4. Results

Demand curves for each operation were transferred to the program and analyzed. When the current toll booth results were examined, it was observed that when the low demand curve was loaded into the program, the delay increased to 108 seconds, and when the medium demand curve was run, the delay increased to 390 seconds. The results for the current barrier toll booth are shown in Figure 5.

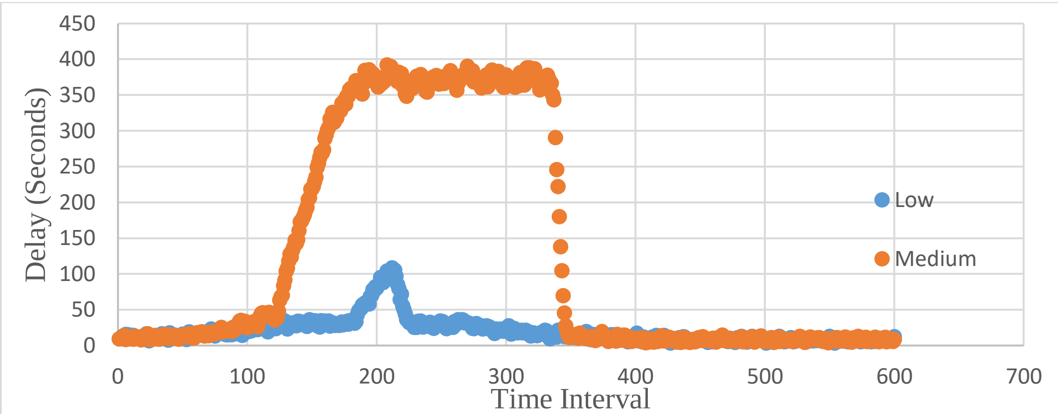


Fig. 5. Current Operation in Low and Medium Demand

The most important reason for this situation is the barrier toll booths. Long queues were observed at the toll booth because service time of cash payment operations is longer than electronic payment. Due to the use of barrier toll booths, delay times remained high for a long time, even when using a medium demand curve. When the high-level demand curve for the current barrier operation was loaded, the number of vehicles could not be loaded sufficiently due to the queue formed. No output could be obtained because the program could not be run efficiently.

After alternative operations were designed, high demand curves were first transferred to the program. In order to examine the effects of barrier use in the first operation, an 8-lane barrier-free toll booth was modeled. In this model, which gave very good results compared to the barrier-operated toll booths, it is seen that the delay value is 130 seconds at the point where demand is maximum. It was observed that one of the most important reasons for the high delay value was the bottleneck. Since the toll booth with 8 lanes continued as 4 lanes, congestion occurred because the capacity of the toll booth is more than the capacity of the road. Three different alternative operations were used to observe the effects of the number of toll booths on delay. When the 10-lane operation was examined, it was observed that the delay value reached 100 seconds at peak times. When the number of lanes was increased even more (12 lanes), it was observed that the delay value reached 109 seconds at peak times. It is seen that as the number of lanes and the capacity of the toll booth area increase, bottleneck congestions become more common. As the optimum operation, the toll booth was designed as 4 lanes. Since this operation was also barrier-free, there was no barrier delay. In addition, as the toll booth is 4 lanes and the road continues as 4 lanes, no bottleneck delays were observed. At the peak of demand, the delay value was observed to be a maximum of 2.5 seconds. The graph comparing the alternative operations is shown in Figure 6.

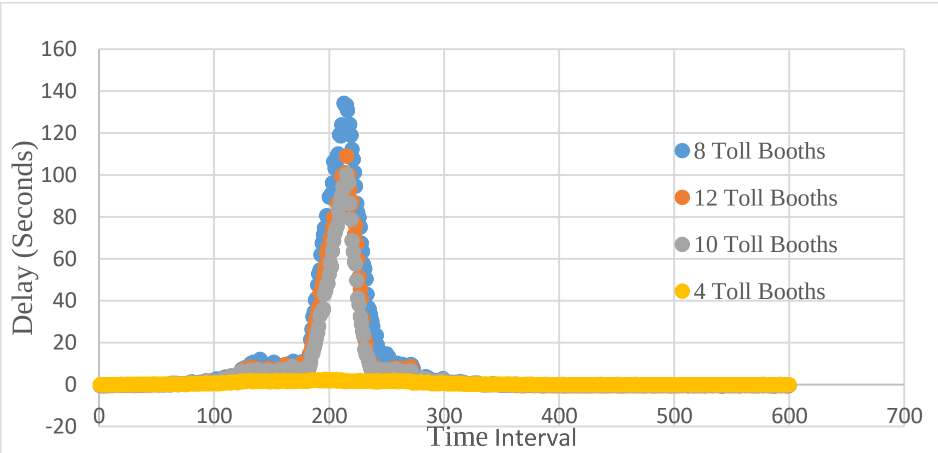


Fig. 6. Alternative Operations in High Demand

Alternative operations were also run by loading medium demand. Almost the same delay values were obtained for the three operations with 12-, 10- and 8-lane toll booths, but not for the 4-lane free passage system. In the former cases, the delay value was observed as approximately 4 seconds during the peak demand period. In comparison, in the operation with the 4-lane free passage system, the highest delay value was observed as 1.33 seconds. The graph comparing these operations is shown in Figure 7.

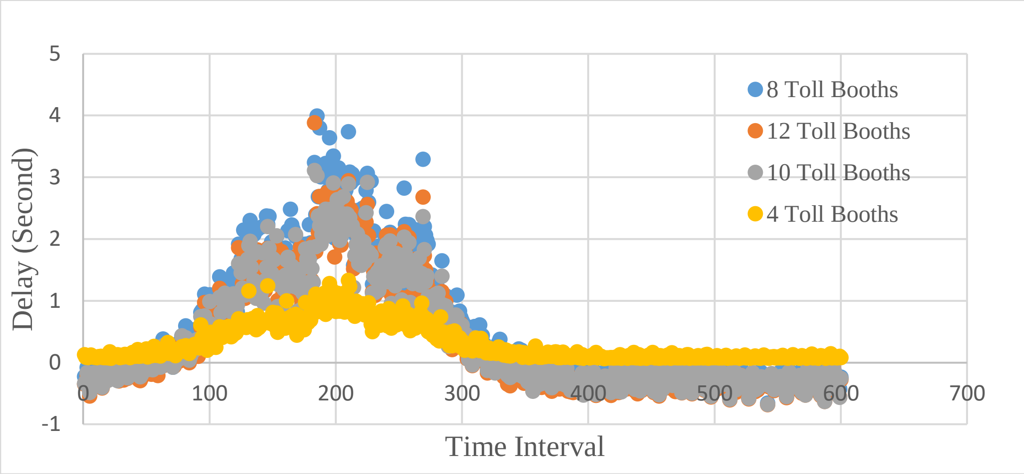


Fig. 7. Alternative Operations in Medium Demand

When the travel time is examined, it was observed that it is affected by both the use of barrier toll booths and the geometry of the toll booth area. In the current operation, it was observed that the average travel time of the vehicles in the A-A' section was 182 seconds during the simulation period of 10.5 hours. When the alternative operations were examined, in the case where the existing toll booth was operated without barriers, the travel time in the relevant section was found as 63 seconds. Travel time for the 10-lane toll booth was found as 59 seconds, and 60 seconds for the 12-lane toll booth. In the operation with a 4-lane free passage system, the average travel time was observed as 35 seconds. When medium demand was loaded, the travel time in the relevant section was observed as 54 seconds in all other alternative operations, but 34 seconds in the 4-lane toll booth operation.

5. Discussion

In this study, the effects of barrier toll booths and toll booth geometry on delay and travel times were investigated. In our study, the Kurnaköy toll booth was modeled using the PTV Vissim micro simulation program. In the current operation, the 8 Kurnaköy toll booths, which are operated with barriers, were compared with alternative operations, and the delay and travel times were analyzed. After the parameters obtained from the video recordings were transferred to the program, each operation was run 10 times for different demand levels. The averages of the ten different simulations were used as data in the study.

It was observed that the toll booth design is inefficient even in the operation where medium demand was loaded on the Kurnaköy toll booths, which have barriers. It was observed that the delay value increased to 390 seconds and the average travel time increased to 182 seconds. When the alternative operations were examined, it is seen that operations modeled as toll booths with 8, 10 and 12 lanes gave better results than the current operation. Significant reductions in delays and travel times were observed. However, in these operations, congestion due to bottlenecks was observed. It was also observed that increasing the capacity of the toll booth increases the congestion at high demand, thus increasing the delay times. When the results of the toll booth operation with a 4-lane free passage system were investigated, delays due to barriers and delays due to bottlenecks were minimized and this operation was found as the optimum operation.

It is anticipated that delay times will decrease with the removal of the barriers at the Northern Marmara Highway toll booths. In order to carry this out, each vehicle must have the necessary equipment to make electronic payment. It is foreseen that with this equipment, barrier-free operation of the toll booths will prevent delays that will occur with the predictable increase in future demand. It is suggested that the geometry of newly designed toll booths should be modeled in a way that does not create a bottleneck. With this modeling, service will be provided with minimal delay even if there is excessive increase in demand.

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