Optimization of Vehicle Volume for Multi Lane Free Flow-Based Contactless Transaction System

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ABSTRACT

This study evaluates the effectiveness of the tapping transaction system using e-toll at the Sidoarjo 2 Toll Gate and analyzes the potential for optimizing vehicle volume through the implementation of a contactless transaction system based on Multi-Lane Free Flow (MLFF). The research method used is quantitative descriptive, with primary data obtained through interviews and observations, and secondary data from government and company documents. Data analysis was carried out using SPSS 26 with the Chi-Square test to determine system stability based on arrival time, service level, and waiting time. The results showed that the highest vehicle arrival rate occurred on Monday, with peak traffic reaching 1,816 vehicles/hour. Although the current system is still optimal under normal conditions, the increase in vehicle volume during long holidays requires additional toll booths. Implementation of MLFF, with transaction times approaching zero, can eliminate queues and significantly improve traffic flow efficiency. This study emphasizes the importance of implementing MLFF at toll gates with high vehicle volumes and recommends further studies on aspects of technology, cost, and risk to ensure a smooth transition. The implementation of MLFF is a crucial step in maintaining long-term operational efficiency and improving toll road performance.

Keywords: *Contactless, E-toll, MLFF, Optimization, Poisson Distribution, Queue Model*

ABSTRAK

Penelitian ini mengevaluasi efektivitas sistem transaksi tapping menggunakan e-toll di Gerbang Tol Sidoarjo 2 serta menganalisis potensi optimalisasi volume kendaraan melalui implementasi sistem transaksi nirsentuh berbasis Multi-Lane Free Flow (MLFF). Metode penelitian yang digunakan adalah deskriptif kuantitatif, dengan data primer diperoleh melalui wawancara dan observasi, serta data sekunder dari dokumen pemerintah dan perusahaan. Analisis data dilakukan menggunakan SPSS 26 dengan uji Chi-Square untuk menentukan stabilitas sistem berdasarkan waktu kedatangan, tingkat layanan, dan waktu tunggu. Hasil penelitian menunjukkan bahwa tingkat kedatangan kendaraan tertinggi terjadi pada hari Senin, dengan lalu lintas puncak mencapai 1.816 kendaraan/jam. Meskipun sistem saat ini masih optimal dalam kondisi normal, peningkatan volume kendaraan selama libur panjang memerlukan tambahan gardu tol. Implementasi MLFF, dengan waktu transaksi mendekati nol, dapat menghilangkan antrean dan secara signifikan meningkatkan efisiensi arus lalu lintas. Penelitian ini menekankan pentingnya penerapan MLFF pada gerbang tol dengan volume kendaraan tinggi serta merekomendasikan studi lanjutan terkait aspek teknologi, biaya, dan risiko untuk memastikan transisi yang lancar. Penerapan MLFF menjadi langkah krusial dalam menjaga efisiensi operasional jangka panjang dan meningkatkan kinerja jalan tol.

Kata kunci: *Distribusi Poisson, E-toll, MLFF, Model Antrean, Nirsentuh, Optimalisasi*

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INTRODUCTION

Indonesia is currently intensively developing infrastructure in various sectors. Based on the Toll Road Regulatory Agency (*Badan Pengatur Jalan Tol*/BPJT), the toll road network was built with the aim of improving connectivity between regions, reducing congestion, and accelerating the movement of goods and people. However, in recent years, many toll roads have experienced a decline in performance, especially on toll roads with high traffic density such as in the capital city of Jakarta and Surabaya, which is caused by congestion and long queues at toll gates, especially on busy days or long holidays. One of the toll roads with the highest Average Daily Traffic (*Lalu Lintas Harian Rata-Rata*/LHR) in East Java is the Surabaya Gempol Toll Road with a volume of 102,390,959 vehicles per year, where according to the General Manager of Office 3 Surabaya Gempol, there are two toll gates on the Surabaya-Gempol toll road that have the highest queue points, namely the Kejapanan Utama toll gate and the Sidoarjo 2 toll gate with LHR data of vehicle volume reaching 31,906 per day and can jump to 47,208 vehicles per day during the Eid period. Long queues on toll roads cause losses of Rp. 4.4 trillion per year so that Toll Road Business Entities need proper management and technological advances to overcome these problems by adopting new technology as one of the important things to influence the implementation of sustainable technology (Wang, 2015).

The current transaction system used in Indonesia primarily relies on electronic toll cards, commonly known as e-toll, in conjunction with the Automatic Toll Gate (Gerbang Tol Otomatis/GTO) toll system. This system generally allows for an average transaction speed of less than 11 seconds, from the moment a vehicle stops to when it begins moving again. However, despite its relatively fast transaction time, the GTO technology system often leads to long queues, primarily due to issues such as damaged or slow card readers. These problems not only cause delays but also reduce the overall efficiency of the toll system. To address these challenges, the country is exploring the adoption of a non-stop (contactless) toll payment system called Multi Lane Free Flow (MLFF). MLFF technology allows for seamless toll payments as vehicles pass through toll gates without stopping, significantly reducing congestion and improving the flow of traffic. By enabling multiple lanes for vehicles, MLFF can accommodate higher volumes of traffic while maintaining efficiency. The successful implementation of MLFF is a major innovation aimed at enhancing the toll payment system's efficiency and effectiveness. However, to ensure its success, careful planning, appropriate resource allocation, and strong coordination among various stakeholders are crucial (Oceania et al., 2024; Nor et al., 2024).

The main issues that need to be addressed are whether the current tapping transaction system using e-toll cards at the Sidoarjo 2 Toll Gate remains optimal and whether the implementation of the MLFF-based contactless transaction system can effectively optimize vehicle volume while reducing queue waiting times. These challenges are critical in ensuring the smooth operation of toll gates, especially during peak traffic periods. From an operational management perspective, the adoption of a more efficient transaction system goes beyond just improving traffic flow. It also plays a significant role in increasing productivity, reducing congestion, and enhancing the overall customer experience. Furthermore, optimizing toll transaction processes can lead to better resource management, such as reducing the need for manual interventions and improving employee productivity. An efficient system also allows for data-based decision-making, which is vital for continuous improvement. By collecting and analyzing data from toll transactions, management can identify patterns, predict peak traffic times, and make informed decisions about resource allocation and system upgrades (Firoozi, et al., 2024). This approach will not only address current issues but also enable the toll system to adapt to future demands and challenges, thus ensuring long-term operational success. This study aims to evaluate the effectiveness of the tapping transaction system compared to the MLFF-based contactless system in improving toll gate operational efficiency.

LITERATURE REVIEW

Definition of Toll Road

Toll roads are part of the general network of alternative roads. "Toll" stands for Tax on Location, which means the application of tariffs when passing through several stops on the toll road. Toll roads are public roads where users are required to pay tolls (Basar & Cetin, 2017). In Indonesia, toll roads began in 1978 and have continued to grow, now covering 2,816 km across Java, Sumatra, Kalimantan, Sulawesi, and Bali (BPJT, 2024). Toll roads and infrastructure play a strategic role in management and economics because they contribute to operational efficiency, productivity, and the economic growth of a country (Kumalasari & Farida, 2024; Hariyanto et al., 2024). Toll roads and infrastructure contribute to economic growth by increasing connectivity, encouraging investment, and accelerating economic turnover (Ke et al., 2020). The transaction system is a mechanism or method used to collect fees (Liana & Fadli, 2023; Roughgarden, 2024). These fees are used to recover capital invested in the construction, maintenance, and operation of toll road infrastructure. Manual Toll Collection (MTC) is a toll fee collection system that involves direct interaction between drivers and toll officers. According to Budiharjo & Margarani (2019), one type of manual toll payment transaction technology is Pay Cash. Pay Cash is a payment technology carried out at toll gates using cash. In modern management practices, the use of Pay Cash has been reduced for reasons of efficiency, transparency, and security (Sarker et al., 2021).

Electronic Toll Collection (ETC) is a technology in toll payments that allows drivers to pass through toll gates without stopping to pay manually, aiming to reduce congestion and speed up the toll payment process (Saif et al., 2023). Currently, in Indonesia, there are two payment transaction methods: e-toll cards (Automatic Toll Booth) and e-toll passes. An e-toll card functions as digital money, and the payment method involves tapping the card at the reader located at the automatic toll booth. An e-toll pass is a toll payment made using contactless technology, which employs AVI (Automated Vehicle Identification) technology for vehicle identification. Some types of technology used in AVI are RFID, ANPR (Radio Frequency Identification), DSRC (Dedicated Short-range Communications), and GNSS (Global Navigation Satellite System). Single Lane Free Flow (SLFF) is a technology system on toll roads that allows vehicles to make toll payment transactions automatically without stopping, but only through one special lane (Budiharjo & Margarani, 2019). SLFF is typically applied in one particular lane where vehicles passing through this lane are detected and automatically charged. The purpose of SLFF is to increase time efficiency and reduce queues at toll gates, although its scale is more limited.

MLFF is defined as a cashless and touchless toll collection system that allows toll road users to pay fares without stopping at the gate when exiting the toll road system. However, there is no retribution mechanism or explanation of the existing technology to support the implementation (Recky, 2021). The procedure for optimizing the implementation of the MLFF system requires Electronic Toll Collection (ETC) technology. The ETC technology to be implemented on several toll roads in Indonesia is the Global Navigation Satellite System (GNSS), which functions similarly to GPS. MLFF is designed as a toll payment transaction system that does not require stopping the vehicle. Unlike SLFF, the MLFF system does not require a barrier, allowing drivers to continue driving through the toll gate, with the transaction process taking 0 seconds (BPJT, 2022).

Optimalization

Optimization is a mathematical framework that focuses on finding the best or optimal solution from a set of feasible options. This best or optimal solution means finding the maximum or minimum value of the objective function while considering the various constraints that exist. According to Ujarari et al. (2024), queuing theory is a mathematical framework designed to analyze queues and improve their efficiency. This approach is applied in various sectors, including telecommunications, transportation, health, and industrial sectors. The theory uses a model that simulates random customer arrivals and service processes, helping to minimize waiting times and improve service provision. Optimization increases the efficiency and effectiveness of resource use to achieve organizational goals (Nuryani et al., 2023; Suryanto & Tyas, 2024).

According to Alfaki et al. (2019), the arrival rate is the average number of customers who arrive per unit of time and refers to how often customers join the queue. The arrival of these customers is assumed to follow a probability distribution process. The distribution that is often used is the Poisson distribution, where this arrival process is random with an average arrival rate of λ. The population reflects the total number of customers who may be in the system. Service level in queuing theory is an important measure used to assess how many customers can be served by a system in a given unit of time (Afolalu et al., 2021). Waiting time is the duration customers spend queuing, which can be minimized through optimal server allocation, while service level is the speed of service provided (Onoja et al., 2018). Service level is expressed in units of vehicles per hour or people per minute. Queue discipline refers to the rules that determine the order in which customers are served or processed in a queue. There are several types of queue disciplines that are commonly used, namely First-In-First-Out, Priority Queue, and Last Come First Served (Rajagukguk & Zarlis, 2019; An et al., 2019). First-In-First-Out (FIFO) is the simplest form, where the first customer to arrive is the first to be served. Priority Queue (PQ) serves customers based on previously set priorities. Last Come First Served (LCFS) serves the last arriving customer. Fourth, Weighted Fair Queuing (WFQ) allocates bandwidth based on weights assigned to various traffic classes.

Queue Model

The queue model that will be used is the Poisson distribution to describe customer arrivals in a system that follows a random arrival process with a constant average arrival rate over a certain time period, and an exponential distribution to provide the probability of the time between events (Haviv & Ravner, 2021). The components used are expressed in Kendall notation (A/B/C/K/N/D). The Single Server Queue Model (M/M/1) has one service channel. This model follows the FIFO queue discipline with a Poisson distribution for vehicle arrivals (λ) and an exponential distribution for service (μ). The maximum number of vehicles in the queue is infinite (∞). The Multi Server Queue Model (M/M/C) adopted in multiple server mode (C) has parallel service channels. Similar to the single server model, this one also follows a Poisson distribution for customer arrivals (λ) and an exponential distribution for service time (μ).

METHODS

The research method used in this study is a descriptive quantitative method (Ramdhan, 2021). This study focuses on the collection and analysis of numerical data to measure the optimal volume of vehicles entering the toll gate when using a contactless transaction system based on MLFF. This method is used to identify the relationship between the use of technology and increased traffic volume. The study was conducted on the Surabaya-Gempol toll road, focusing on the Sidoarjo 2 exit toll gate. Data collection was based on primary data through interviews and observations, and secondary data including online data, government and company documents, and scientific publications. The data were analyzed using SPSS 26, with the Chi-Square test. The decision rule was as follows: if the significance value (sig) > 0.05, then Ho is accepted (Poisson or exponential distribution); if the sig value < 0.05, then Ho is rejected (not Poisson or exponential distribution). The results of the data processing were analyzed based on arrival time analysis, service level analysis, waiting time analysis, and optimal toll road analysis. The utilization stability values (ρ) were interpreted as follows: $\rho < 1$ = Stable system, $\rho \approx 1$ = Almost full capacity, $\rho > 1$ =

Unstable system, where congestion occurs. Optimal vehicle volume analysis used the following characteristics: $\rho \approx 0.8$ - 0.9: The system operates with high efficiency, the average queue time is short, service capacity is almost optimal, and there is no long-term vehicle congestion; $\rho > 1$: Vehicle volume exceeds system capacity, resulting in congestion.

RESULTS

The Surabaya-Gempol toll road connects Surabaya and Gempol in East Java, with a focus on the Sidoarjo 2 toll gate, which experiences heavy traffic and long queues. In March 2024, the average daily traffic volume (LHR) was 30,972 vehicles. Located at km 756+000 on the Porong-Gempol section, the toll gate faces congestion during rush hours and holidays, with queues extending 200-500 meters, exceeding the minimum service standard of 10 vehicles (160 meters). The toll gate features a barrier system, where a horizontal automatic barrier opens after payment. There are 4 multi-toll booths that accommodate vehicles of all classes and 2 main booths with 7 single booths for light vehicles only. The payment process uses e-toll cards with a closed transaction system at each booth. The queue follows an M/M/C model, where vehicles randomly select booths for service.

Table 1. Arrival Rates on GTO Single and GTO Multi

Gate	Day	Time	GTO Single (vehicle/hour)	GTO Multi (vehicle/hour)
GTO -Single	Sunday	07.00-08.00	394	788
	Sunday	10.00-11.00	372	744
	Monday	07.00-18.00	445	890
	Monday	10.00-11.00	398	796
GTO Multi	Sunday	07.00-08.00	227	908
	Sunday	01.00-11.00	189	756
	Monday	07.00-08.00	405	1620
	Monday	10.00-11.00	454	1816

The highest vehicle arrival rate occurs on Monday from 07:00 to 08:00 for GTO Single and from 10:00 to 11:00 for GTO Multi. GTO Single is analyzed based on the arrival rate per substation and for two main substations, while GTO Multi is analyzed per substation and for four main substations. The Chi-Square test results show a significance value of 1.000, which is greater than 0.05. Thus, the null hypothesis (H_0) is accepted, indicating that the vehicle arrival data follows a Poisson distribution. This means that the vehicle arrival pattern is random with a certain probability according to the distribution.

Table 2. Traffic Intensity Ratio at Single Substations and Multi Substations

Gate	Day	Time	λ (vehicle/hour)	ε (Gate)	μ (vehicle/hour)	ρ
GTO -Single	Sunday	07.00-08.00	788	2	611,21	0.64
	Sunday	10.00-11.00	744			0.61
	Monday	07.00-18.00	890			0.73
	Monday	10.00-11.00	796			0.65
GTO Multi	Sunday	07.00-08.00	908	4	611,21	0.37
	Sunday	01.00-11.00	756			0.31
	Monday	07.00-08.00	1620			0.66
	Monday	10.00-11.00	1816			0.74

The observation results show that the average transaction time is 5.89 seconds. The Chi-Square test of the transaction time data produces a significance value of 1.000, which is greater than 0.05. Thus, the null hypothesis (H_0) is accepted, indicating that the transaction time data follows an exponential distribution. The level of service obtained is 611.21 vehicles per hour. Analysis of the traffic intensity ratio ($\rho < 1$) shows that the system is not congested, meaning that both GTO Single and GTO Multi can handle vehicle arrivals without long queues or congestion.

Table 3. Probability of no vehicle in the system Po and Pn

Gate	Day	Time	λ (vehicle/hour)	ε (gate)	μ (vehicle/hour)	ρ	ρ0	ρn
GTO-Single	Sunday	07.00-08.00	788	2	611.21	0.64	0.2175	0.2158
	Sunday	10.00-11.00	744			0.61	0.2300	0.1773
	Monday	07.00-18.00	890			0.73	0.1807	0.3444
	Monday	10.00-11.00	796			0.65	0.2138	0.2249
GTO-Multi	Sunday	07.00-08.00	908	4	611.21	0.37	0.2243	0.2243
	Sunday	01.00-11.00	756			0.31	0.2769	0.2769
	Monday	07.00-08.00	1620			0.66	0.0921	0.0921
	Monday	10.00-11.00	1816			0.74	0.0739	0.0739

The probability analysis reveals that the lowest probability occurs on Monday from 07:00-08:00 WIB at GTO Single and 10:00-11:00 WIB at GTO Multi, indicating that the queue system is constantly busy with no idle time for servers. The highest probability occurs during the same hours, suggesting the system is often or nearly at full capacity. When vehicle volume is low, the system's utility level is also low, making the use of the substation suboptimal. In this condition, queues or vehicle buildup are rare, as the system is not overloaded.

Table 4. Average Waiting Time in Queue (Wq) and W in GTO single and GTO Multi

Gate	Day	Time	λ (vehicle/hour)	ε (gate)	μ (vehicle/hour)	ρ	ρ0	Wq (hour)	W (second)
GTO-Single	Sunday	07.00-08.00	788	2	611,21	0.64	0.2175	0.0011	9.72
	Sunday	10.00-11.00	744			0.61	0.2300	0.0009	9.0
	Monday	07.00-18.00	890			0.73	0.1807	0.0022	13.65
	Monday	10.00-11.00	796			0.65	0.2138	0.0012	18.24
GTO-Multi	Sunday	07.00-08.00	908	4	611,21	0.37	0.2243	0.000467	6.05
	Sunday	01.00-11.00	756			0.31	0.2769	0.000283	5.97
	Monday	07.00-08.00	1620			0.66	0.0921	0.006674	8.90
	Monday	10.00-11.00	1816			0.74	0.0739	0.001446	11.10

The highest waiting times at Sidoarjo Toll Gate 2 occurred on Monday from 07:00-08:00 WIB at the single GTO with 7.92 seconds and from 10:00-11:00 WIB at the multi GTO with 5.20 seconds. The longest waiting durations were recorded at the same times, 13.65 seconds for the single GTO and 11.10 seconds for the multi GTO. Despite these longer waiting times, they were still close to the standard service performance time (SPM) of 11 seconds. Overall, the current system is efficient and can serve customers well without significant queuing.

Table 5. Number of Vehicles in Queue and Number of Data in the System at GTO Single and GTO Multi

Gate	Day	Time	λ (vehicle/hour)	ε (gate)	μ (vehicle/hour)	ρ	ρ0	Lq (vehicle)	L (vehicle)
GTO-Single	Sunday	07.00-08.00	788	2	611,21	0.64	0.2175	1	2
	Sunday	10.00-11.00	744			0.61	0.2300	1	2
	Monday	07.00-18.00	890			0.73	0.1807	2	3
	Monday	10.00-11.00	796			0.65	0.2138	1	2
GTO-Multi	Sunday	07.00-08.00	908	4	611,21	0.37	0.2243	0	2
	Sunday	01.00-11.00	756			0.31	0.2769	0	1
	Monday	07.00-08.00	1620			0.66	0.0921	1	4
	Monday	10.00-11.00	1816			0.74	0.0739	3	6

The results show that the largest number of vehicles in the queue occurs on Monday at 07.00-08.00 WIB at GTO single with the number of vehicles queuing of 2 vehicles and at 10.00-11.00 WIB at GTO multi with the number of vehicles queuing of 3 vehicles. This shows that vehicles do not wait too long in the queue so that there is no buildup which shows that the existing substation is still sufficient to meet service needs. The results show that the system works harder on Monday at 07.00-08.00 WIB at GTO single with the number of vehicles queuing of 3 vehicles and at 10.00-11.00 WIB at GTO multi with the number of vehicles queuing of 6 vehicles. This shows that at that hour there are many vehicles in the system simultaneously, both those being served and those waiting in the queue because the arrival rate is greater than its service capacity (Hayati & Barus, 2023). Analysis of the Optimal Number of Booths at the Sidoarjo 2 Toll Exit Gate Assuming the arrival rate increases 3 times as many as 5670 vehicles with 4 booths and an average of 611.21 vehicles per hour, the intensity is 2.3. The results of the analysis show that the intensity ratio exceeds the optimal limit $\rho > 1$ so that congestion and long vehicle queues occur. If the high vehicle volume occurs continuously, it is necessary to add booths. The assumption of adding booths is n ($n > c$) = 10 booths. Analysis of the Optimal Number of Booths at the Sidoarjo 2 Toll Exit Gate Assuming the arrival rate increases 3 times as many as 5670 vehicles with 10 booths and an average of 611.21 vehicles per hour, the intensity is 0.92. If the vehicle volume increases 3 times, the number of booths needs to be increased by 6 booths to 10 active booths to get an intensity ratio of $\rho<1$ so as not to cause congestion and long queues.

Optimal Vehicle Volume Analysis at Sidoarjo 2 Toll Gate Exit. The calculation is taken from the highest number of vehicles from the results of field observations. Capacity (max) is 2444.84 vehicles. Optimal vehicle volume: this volume must meet the intensity ratio $\rho<1$ with the characteristics of optimal vehicle volume $\rho \leq 0.8$-0.9 so that the optimal number is 1955.87 vehicles/hour. So, the optimal vehicle volume is 1955 vehicles/hour with a capacity of 4 booths so that the system can handle services efficiently without causing congestion or congestion. Implementation of MLFF-Based Contactless Transaction System at Sidoarjo 2 Toll Gate Exit. The results show that the application of MLFF-based contactless technology to the transaction system at the Sidoarjo 2 toll gate exit is very efficient and effective because with a vehicle volume of 1816 and a transaction time of 0.05 seconds, it obtains a very minimal intensity ratio $\rho<1$ so that the system can serve vehicles optimally (Sari et al., 2018). This system also eliminates vehicle waiting time in queues and in the system by reducing delays by 0 seconds and can eliminate the number of vehicles in queues and in the system so that with the MLFF-based contactless transaction system, the optimal volume of vehicles entering is unlimited and does not cause congestion.

CONCLUSION

The formulation of the problem and the results of the analysis, it can be concluded that the highest arrival rate at the Sidoarjo 2 toll gate exit occurs on Monday from 07:00 to 08:00 WIB at the single GTO with 890 vehicles/hour and from 10:00 to 11:00 WIB at the multi GTO with 1,816 vehicles/hour, with an average transaction time of 5.89 seconds per vehicle. With the current number of booths, the system is still optimal in serving vehicles arriving at the toll gate. However, if there is an increase in vehicle arrivals, such as during long holidays when vehicle volume triples compared to normal periods, an additional 6 booths are needed (based on the calculation of the largest vehicle volume at the multi-booth). The optimal vehicle volume that can be served by the system, while maintaining the characteristics of $\rho < 0.8$–0.9, is 1,955 vehicles/hour (calculation of the largest vehicle volume at the multi-booth). The implementation of a contactless transaction system based on MLFF, with a transaction time of 0 or 0.05 seconds, can work optimally by reducing the delay time to 0 seconds, with no vehicles queuing, ensuring smooth traffic flow. The implementation of MLFF is necessary at toll gates with high vehicle volumes, and further studies are needed on the MLFF system, particularly related to technology, costs, and risk analysis.

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