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Modelling toll traffic pattern: the Jagorawi toll case study

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Abstract. The aim of this study is to investigate the impacts of, such as conventional, automatic toll gate with e-toll card (GTO) and On-Board Unit with Multi Lane Free Flow (MLFF) payment system on the level of queuing, such as the number of cars in queue, the amount of queue time, and the congestion costs due to queue. The queuing theory was used to compare the performance of different payment system on Jagorawi toll roads as a case study. A model was developed to understand the pattern of queue and the relationship between queuing pattern, the toll's gate volume, and the number of booth. This study found that congestion occurred in the majority of the toll gate, which heavily due to unreliability of the booth services. Rather than increasing the number of booth, simulation of queuing models showed that optimization of toll gate could be achieved with GTO systems. The findings showed that the total number of cars and time in queue at cash payment system is almost 540% higher and annual congestion cost is almost 284% higher than GTO.

1. Introduction

Toll road serves the purpose of high mobility and accessibility. Currently, there is 34 toll roads in Indonesia with total length 987 km, serve 3.7 million vehicles daily on average. The National Development Mid-term Plan (2015 – 2019) has targeted toll road development for 1,807 km in 2019 [1].

While new toll road construction is progressively developing, current issues are related with the establishment of new payment system with electronic toll card (ETC), which targeted all toll booths to be cashless by 100% in the end of 2017 and the shift of the payment system into the multilane free flow by 100% in the end of 2018.

The Ministry of Public Works Regulation in [2] has assigned the minimum service standards on toll accessibility for Indonesia's toll. In relate with the toll payment system, the minimum service standard sets the average transaction speed of maximum 6 second per vehicle on an open transaction, while the close transaction should serve at maximum 5 second per vehicle on the entrance and maximum 9 second per vehicle on the exit. It is believed the implementation of ETC and high speed tolling by Jasa Marga and Indonesian Toll Road Authority or BPJT is a direct strategy to achieve these standards. The ETC system is expected to increase the transaction speed by reducing the transaction period, at the service

standard of maximum 4 second per vehicle on take toll ticket and maximum 5 second per vehicle on transaction. The maximum number of queue in toll booth should be no more than 10 vehicles per booth at a normal traffic condition.

The Greater Jakarta tolls currently serve 47% share of toll traffic. Jasa Marga has officially introduced this new non-cash payment system in Jagorawi since 12 September 2017. The implementation of this policy was gradually applied on all Jakarta-Bogor-Ciawi toll gates and was completed on 26 October 2017 [3].

In order to understand the impact of this ETC payment system on toll road performance, the comparison of the new and conventional payment system applied in Jagorawi toll was investigated. This research aims to understand the impact of varied payment system on toll performance in term of the queuing level. A model is developed to analyze the relationship between queuing, the toll's gate volume, and the number of booth or toll booth. The output of the model will help to identify when and where toll gate to be upgraded into GTO (the automatic gate) and non-gate or high speed tolling system with MLFF (multilane free flow). The model will also analyze the optimum booth number when the single system of the mix system (hybrid gate) to be applied.

2. Methodology

2.1. Research approach

Indonesian toll currently served by 261 toll gates that consisted of 1,484 toll booths. There are three payment system, which is consist of manual gate with cash payment, hybrid gate that combine cash and electronic card, and the automatic gate or GTO that required tapping electronic card on payment and using e-card plugged in to the OBU.

The e-payment issue consists of the adaptability and the acceptability from toll users on e-payment system, required the gradual implementation and the application of hybrid method on payment and the optimum action plan on full application of ETC and MLFF.

This research investigates the optimum choice of location, timing, and the number of toll booths when the single e-payment or hybrid to be applied. The approach on this investigation consists of comparing the impact of each and combination of payment system on the toll performance, especially by considering the minimum service standards. There are three performance indicators to be compared from the application of each payment system, i.e. the number of vehicle in queue, the amount of queue time and the implication of queue on congestion costs. An input data consisted of one variable: the seven days toll gate volume pattern in 6 (six) toll gates in Jabodetabek: Bogor, CIbubur, Taman Mini, Dukuh, Cimanggis Utama and Gunung Putri; from 18 to 25 September 2017 that consisted of hourly gate volume from total 69 booths [4].

A model is developed to investigate the relationship between the queuing level, the minimum service standard on maximum allowable time of transaction period in second, and the minimum service standard on maximum allowable number of vehicle in queue. A regression model is developed to predict the optimum number of toll booths as a function of the hourly toll gate volume in each toll booth.

The stages of this research is explained as in Figure 1. Firstly, given the hourly toll gate volume data in the case study, identification of toll traffic pattern based on daily pattern was described by statistic descriptive [5][6]. Secondly, the queuing model was established based on input data (volume of vehicle per booth per hour or λ), the service rate (an assumption of the transaction time for each payment system, hence refer to the number of vehicle exit the toll booth or μ), the threshold value when $\lambda = \mu$ [7]. The queuing formula will calculate the level of queuing in terms of the number of vehicle in queue per hour. Thirdly, the extension of the model by including other variables, such as the queuing time and the congestion costs of queuing. We assigned some assumptions to produce those variables, such as the queuing capacity in one hour according to the service rate of each payment system and the value of time calculated based on the monthly minimum wage level in Jabodetabek (IDR 3.6 million). Finally, a regression equation was developed to predict the number of required toll booth as a function of the gate volume per hour.
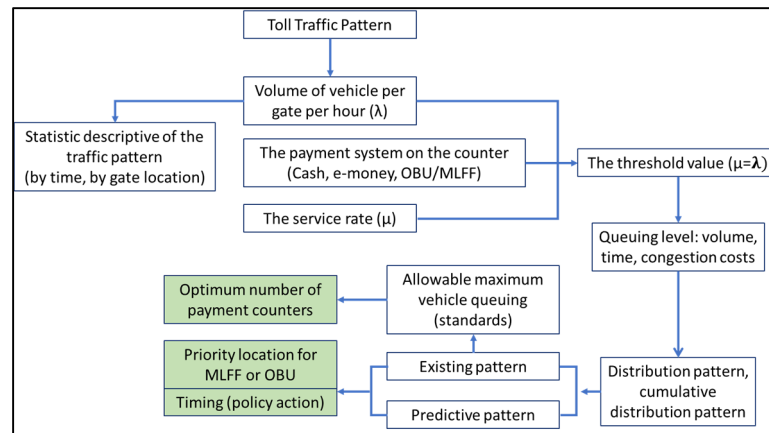
Figure 1. Research methodology

2.2. Queuing theory
The queuing model applied in this research was referred to the formula discussed in [7]. The basic formula was written as follows:

$$n = \left(\frac{\lambda^2}{\mu*(\mu-\lambda)} \right) \tag{1}$$

Where n is the number of vehicle in queue per hour in each toll booth; λ is the volume of vehicle per hour entry the toll booth; μ is the capacity of the toll booth to serve vehicle according to the service rate of each payment system, i.e. 11 seconds per vehicle in the cash system, 8 seconds per vehicle in the GTO system, and 6 seconds per vehicle in the MLFF system.

To simulate the optimum number of payment booth for each toll gate, some constraints was assigned, such as the maximum number of vehicle in queue according to the minimum service standards and the assumption of uniform queuing distribution across all payment booths in one toll gate, hence $\lambda\_1=\lambda\_2=\lambda\_3=\cdots=\lambda\_m$, where m is the existing number of payment booths.

(a)   (b)
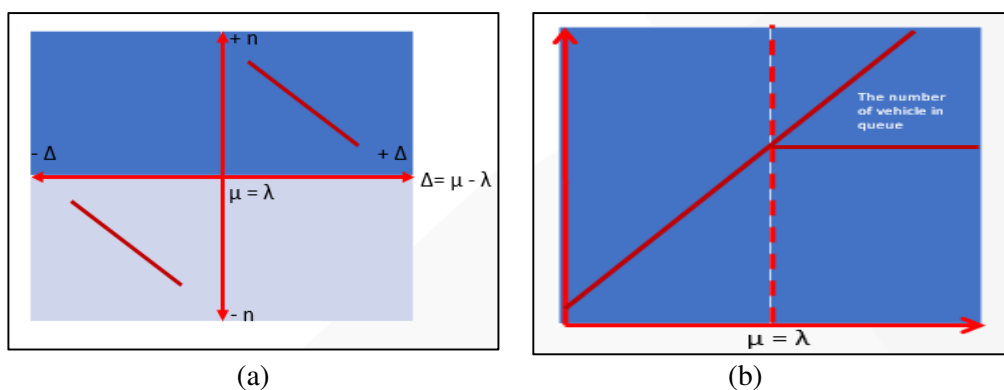
Figure 2. Visualisation of the equation 1. (a). Relationship between the number of vehicle in queue, arrival to the queue and the service time. (b). The threshold of queuing time and its impact on the level of queuing.

Figure 2 (a) explained the hypothetical relationship between the number of vehicle in queue and the second component of the denominator in equation 1. The higher positive differences between μ and λ means the lower number of vehicle in queue. The large negative differences between μ and λ means the lower space left on toll gate per hour. Figure 2 (b) illustrated the queuing began to accumulate once the

threshold value has been achieved, and the remaining vehicle in queue in a given hour t will be accumulated in the hour t+1.

The predictive model also developed by a single regression, based on a relationship between the number of vehicle in queue and the volume of toll booth per hour based on data. The predictive model was used to simulate the optimum number of toll booths based on a single or a hybrid payment system in each toll gate and when this particular toll gate should implement the MLFF in the future.

2.3. Study area

Figure 3 presented the study area, the Jagorawi toll road network that consisted of 14 toll gates overall. The case study specifically was focused on 6 (six) toll gates i.e. Bogor, Cibubur, Taman Mini, Dukuh, Cimanggis Utama and Gunung Putri, accounted for 69 toll booths.

Jagorawi toll road network currently covered 59 km length. It served total 550,000 daily traffic on average (2016). The six toll gates being studied have around 220,000 daily traffic (September, 2017). The implementation of cashless payment in Jagorawi was among the first in Indonesia that were started since 18 September 2017, where the first period of cashless payment was gradually implemented during 15 September – 28 September 2017.

1. Ciawi
2. Bogor
3. Sentul Selatan
4. Sentul
5. Citeureup
6. Gunung Putri
7. Cimanggis
8. Cimanggis Utama
9. Cibubur
10. Pasar Rebo
11. Dukuh
12. TMII
13. Cililitan
14. Cawang
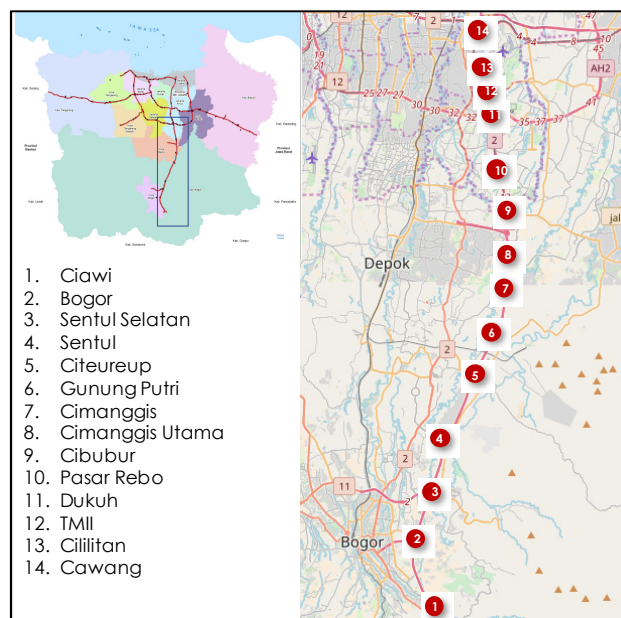
Figure 3. The study area: the Jagorawi toll network

3. Results and discussion

3.1. Traffic pattern at toll gate

The pattern of traffic at toll gate Cibubur and Gunung Putri on weekdays from 19 to 25 September 2017 are shown in Fig 4. It can be seen that the pattern for each toll gate is almost similar. Similar findings were found from the other Jagorawi toll gates.
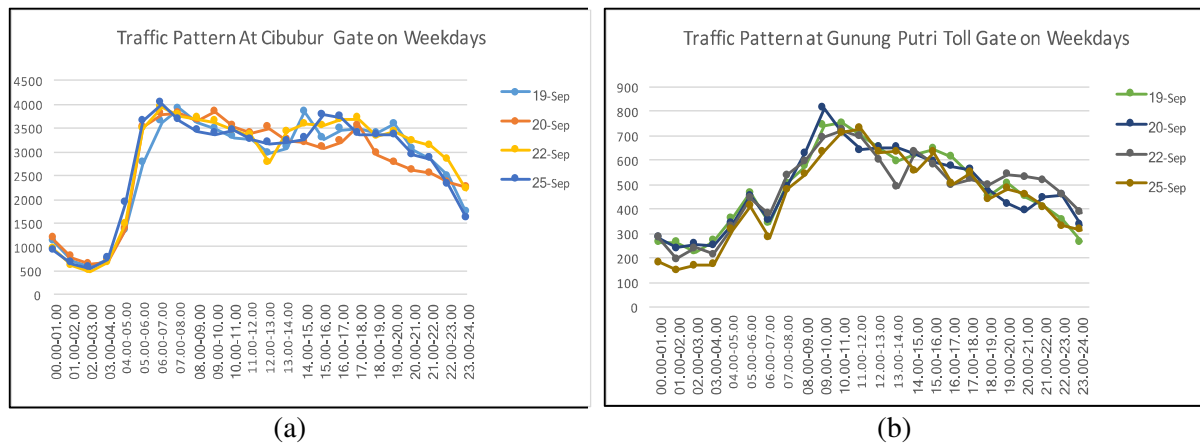
(a)   (b)

Figure 4. Traffic pattern on Weekdays. (a) at Toll Gate Cibubur and (b) at Toll Gate Gunung Putri

As the pattern for the weekdays is similar, in the next analysis, data on the September 18, 2017 will be use as representation of the weekday data at all toll gates.

Figure 5 shows the distribution of traffic at each booth at Cibubur Toll Gate on the September 18, 2017 where the traffic was not equally distributed among the booths. One booth was more favorable than the others. This phenomenon may be due to the booth has been upgraded from cash system to automatic payment system. However, no data available to support this assumption.
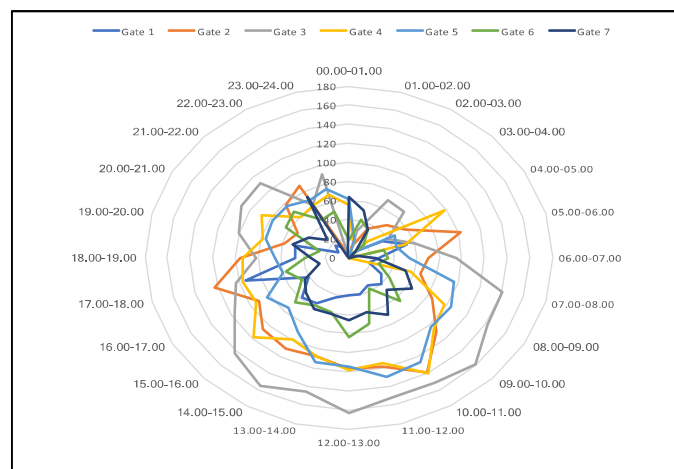
Figure 5. Distribution of traffic at each booth at Cibubur Toll gate

3.2. Queue analysis

Using queueing formula in equation (1), the number and the time of vehicle in queue was estimated for each type of payment system i.e. cash, GTO and MLFF at morning and evening peak hour. The estimation was made for six major toll gates such as at Cibubur, Bogor, Gunung Putri, Cimanggis Utama, Dukuh, and Taman Mini. The results were compared to the maximum number of vehicle in queue according to the Minimum Standard of the Service which is 10 vehicles. The results are shown in Fig. 6.
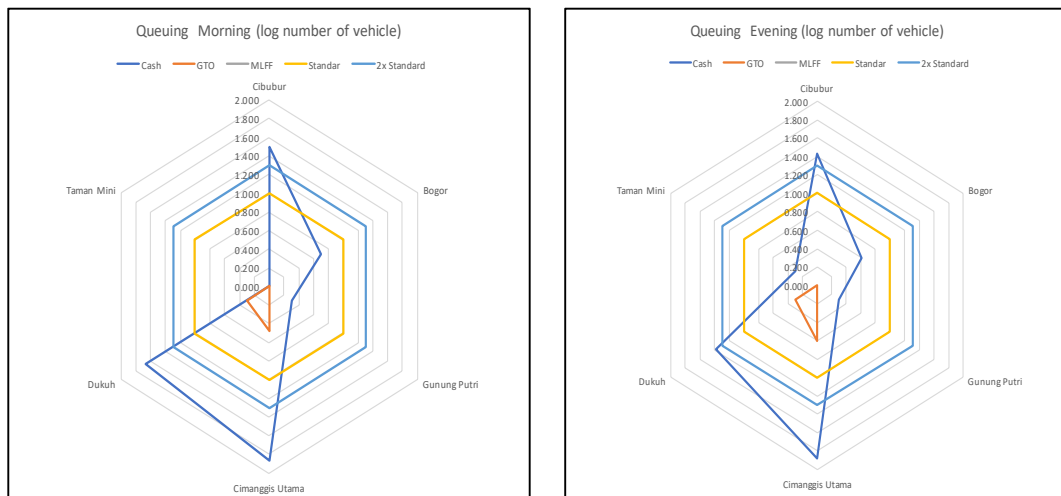
Figure 6. Comparison of queue for each type of payment system and the minimum operational standard

Both graphs are showing similar pattern where cash payment system would not be able to meet the minimum standard of services for the Cibubur, Cimanggis Utama, and Dukuh Toll gates. The number of vehicles queuing even exceeds twice of the maximum number of vehicles allowed in the Minimum Standard of Services. However, at the other toll gates such as Bogor, Gunung Putri, and Taman Mini, the number of vehicle in queue was lower than the maximum allowable.

The implementation of the GTO at the toll gates of Cibubur, Cimanggis Utama and Dukuh was predicted to reduce significantly the number of vehicle in queue. All of the toll gates would meet the requirement mentioned in the standard.

3.3. Congestion price

Total loss due to the payment system annually was estimated using congestion pricing formula. The result is shown in Fig. 7. The toll gate with the highest total loss was Cibubur, which was estimated to be IDR 84 Billion, followed by Cimanggis Utama with IDR 49 Billion and Dukuh with IDR 21 Billion.
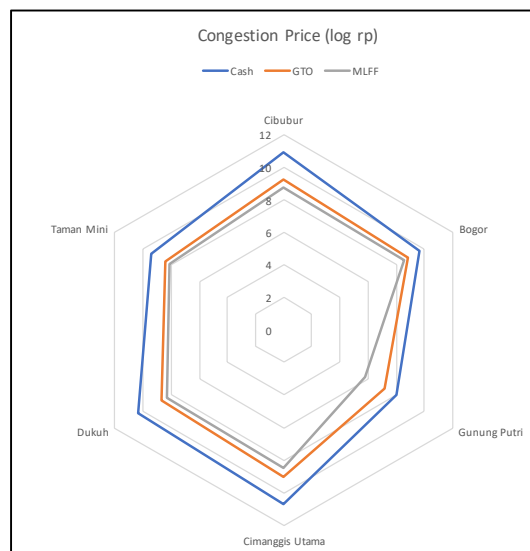
Figure 7. Annual congestion price at the toll gates

3.4. Modelling and Simulation for Estimation of the Required Number of Booth

In order to estimate the number of required booth, a model was developed. The model was a linier model between number of vehicle and the number of booth required.
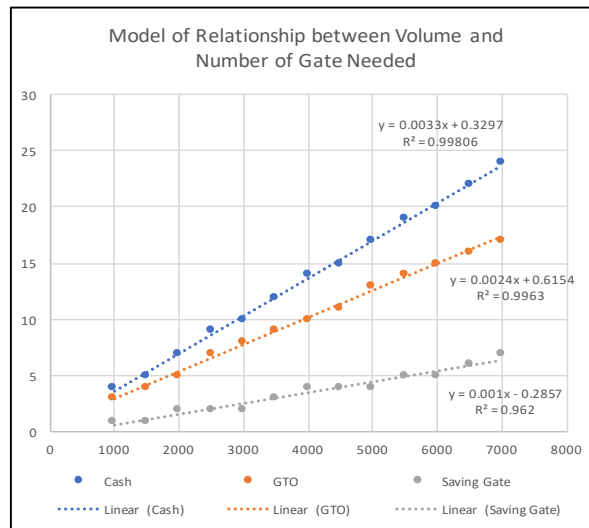

**Figure 8.** Model of the relationship between Traffic Volume versus number of required booth

Based on the model, the number of booth can be predicted based on the system used and total vehicle enter the gate. For example, when using cash payment system with the number of vehicle enter the gate was 6000, total booth needed would be 20, but if only GTO was used, total number of booth needed would be 15.

The model in Fig. 8 could be used to estimate number of booth required if a combo system will be implemented. If a combination between GTO and cash system will be used, number of counter needed would be depended on the distribution of vehicle entering the payment system. For example, if 2000 from 6000 people will choose GTO, number of required is 5 GTO and around 10.

Based on the model, the booth needed for Cibubur and Cimanggis Utama gates when single system was used for year 2017, 2020, 2025, 2030 and 2035 are shown in Fig. 9. The total vehicle enter the gate was assumed to increase by 8% per-year and the number vehicle at each booth was assumed to be uniformly distributed.
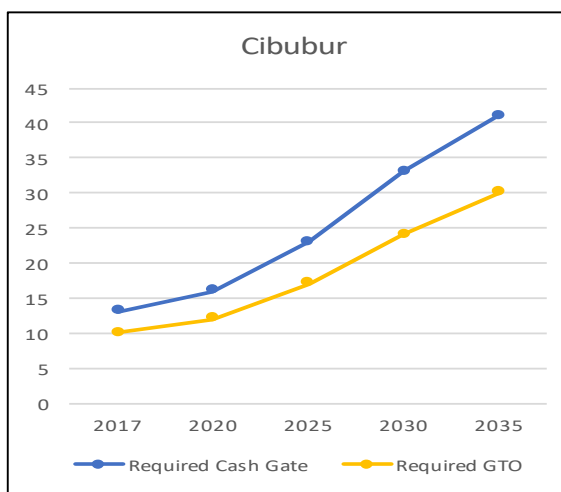
(a)
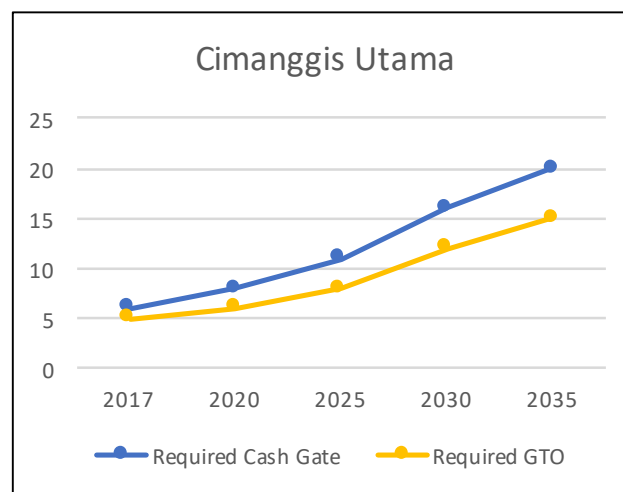
(b)

Figure 9. Number of booths needed in the future when single payment system is used. (a) Cibubur, (b) Cimanggis Utama.

The existing booths for the toll gate Cibubur, Bogor, Gunung Putri, Cimanggis Utama, Dukuh and Taman Mini are 17 and 7 respectively. From Fig. 9 we could see that the existing number of booth when using cash payment system would not be enough at Cibubur and Cimanggis Utama in 2020 if the traffic is equally distributed among the counters. When all of the payment system was upgraded to GTO, number of the booths would be enough until 2025.

4. Conclusion
A simulation of the performance of toll gate with difference type of payment system has been conducted. It can be concluded that the cash payment system should be upgraded to GTO or MLFF for the Cibubur, Cimanggis Utama and Dukuh gates, because the use of cash system at those toll gates were proven to be unsatisfied the Minimum Standard of Services and potentially to cause of billion-rupiah loss due to the congestion at the gate.

5. References
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