

The Empirical Study on the Impact of Road Gradient and Truck Composition on the Toll Road Traffic Performance

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Abstract. The Jakarta Outer Ring Road (JORR) is a toll road system that circles the outskirts of Jakarta, where the purpose of this road is to reduce congestion on the street network of the city centre of Jakarta. However, the high composition of trucks in JORR resulted in congestion, and moreover it is suspected that the steep gradient of this road has contributed to this situation. This study aims to investigate the impact of road gradient on the trucks and the overall traffic performance from macroscopic view point. This study is the complement to a similar study that has been done in JORR previously, to confirm the result. The previous study was based on the Vissim simulation, while this paper will be entirely focused on an empirical study. Using the data obtained from 24-hour traffic recording on selected JORR sections that represent various gradients, traffic flow models are generated, and the effect of gradient could be assessed. The speed difference between trucks and non-trucks shows 56.2%~127% gap as the result of different gradient occurred. The overall free flow speed (uf) difference of different gradient is up to 27.3%. This result will benefit to the transport authority to justify the policy concerning the existence of trucks in the traffic flow, particularly in the condition at which trucks are regarded as a culprit of traffic congestion.

Keywords. Road gradient, trucks, truck composition, toll road, Jakarta Outer Ring Road

1 Introduction

Jakarta as the capital city of Indonesia has over 10 million inhabitants. It reaches up to 20 million if combined with the other Jakarta metropolitan area (Jakarta, Bogor, Depok, Tangerang, and Bekasi) or it is equal to 10% of the total population of Indonesia. With that number of people, around 70% of the money is being circulated in Jakarta. Thus, the economic productivity must run smoothly without facing serious obstacle. However, Jakarta and its traffic congestion have been slowing down the economic productivity.

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People are getting late for work, freight carriers are not able to deliver on time. Therefore, many solutions are being made to reduce the congestion and one of those is the toll road construction. Toll road is built to provide a better service than the arterial road. Jakarta Outer Ringroad (JORR) is a toll road system that link Jakarta and its metropolitan area. Yet the toll road that been built since 1990s is still less satisfactory. One of the factors that said being the cause of it is that it is being used as the main road for freight transport as it links to Soekarno-Hatta International Airport (SHIA) and integrated with Tanjung Priok toll road system. Heavy vehicle (i.e. trucks) need more space due to their large dimensions and relatively have lower speed than passenger cars especially when the road has steep grades. As the result, JORR operator is planning to restrict trucks to pass during a certain time. On the other hand, logistics users will be at great loss while one of the reasons of the toll road construction is to improve freight deliveries. Due to that matter, further research is needed to fully understand the impact of road gradient and truck composition on the toll road traffic performance specifically in Jakarta Outer Ringroad (JORR).

Studies about traffic performance associated to the road geometry condition, especially the road gradient, have been widely done. It shows the speed of the heavy vehicle in the uphill grade is slower than passenger cars [1]. This speed difference created delays and reduce the traffic performance of the road [2]. The research then presented as traffic models which shows the correlation between speed, flow and density [3] [4]. Another study shows that due to speed difference, heavy vehicles need to have a special lane for it not only to improve the traffic performance but also for safety purpose [5].

Studied about similar case was done but using a simulator application called VISSIM in which some factors are being assumed [6]. VISSIM is microscopic simulation software thus it observes the performance of the individual heavy vehicle with other. On the other side, heavy vehicle may have different effect on the overall traffic performance. This research purpose is to investigate the impact of heavy vehicle composition on the traffic performance in JORR in macroscopic way. It is also compare different road gradient so it expected to get a rationale of route shifting for heavy vehicle to avoid steep gradient.

2 Research methodology

Data collection was initiated by 48-hour traffic recording by video camera on selected JORR section, which is 100 m length and 3.5% of road longitudinal gradient. The data were obtained from the recording videos by determining a certain starting and ending lines as illustrated in Fig.1.



Fig. 1. Situation at the observation segment

The data recording then processed by tracing vehicle (divided into four types; light vehicle, medium heavy vehicle, large bus, and large truck) in time and space as it passed the section. The section under consideration is 4-lane divided road including the shoulder. The data collection then gathered into Excel sheets and processed to obtain the three macroscopic traffic stream characteristics, namely volume, speed and density. The observation period is sliced into 5-minute interval to get the flow rates. For each vehicle type, speed was calculated from the sample of vehicle that crossed the section during the time interval. The sample then randomly picked during the time interval. From the data of volume and speed the traffic density was derived, and mathematical models are developed to describe the relationship among the traffic flow variables, using the regression technique. The first 24 hour observation data is used for calibration process and $\pm 20\%$ of the second 24 hour observation data is applied to validate the model through Pearson correlation test using XLSTAT of Excel. The validated model then will be compared with the previous models that represent 0% and 2% of road gradient in the same toll road system (JORR) [6] [7].

3 Result and discussion

3.1 Speed, Density and Volume Characteristics

The 24-hour recording counted as 288 data of 5-minute interval observation. Fig.2 describes the pattern of traffic density per 5 minutes interval, speed of heavy vehicle and speed of non-heavy vehicle. The data then divided into 4 time group, namely 00.00-05.00, 05.01-16.00, 16.01-21.00, 21.01-24.00. The mean of volume, density, and speed (non-heavy vehicle and heavy vehicle) is shown in Table 1. From midnight to early morning (00.00-05.00) the average density is 28 pcu/km, average volume is 1073 pcu/hour and average speed for non-heavy vehicle is 88 km/hour and average speed for heavy vehicle is 49 km/hour. At this period, the vehicles have more space for movement, so the speed difference between non-heavy vehicle and heavy vehicle is quite big. The next time group, namely 05.01-16.00, the average volume is increased to 3264 pcu/hour and average density is 73 pcu/km, the average speed is also increased to 93 km/hour for non-heavy vehicle and 71 km/hour for heavy vehicle.

This shows that the road still has yet reach its capacity but the impact of the increase of density is the speed between the two types of vehicle is narrower.

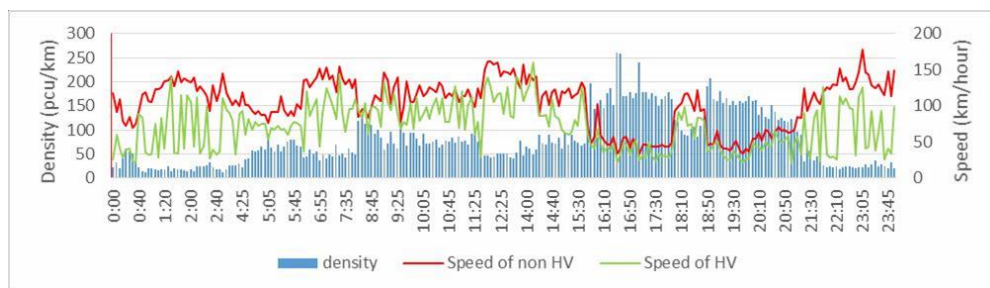


Fig. 2. Density, speed of NON HV and speed of HV

Table 1. Average volume, density, speed of NON-HV and HV of four time groups

Period of Observation	Average Volume (pcu/hour)	Average Density (pcu/km)	Average speed of Non-HV (km/hour)	Average of speed of HV (km/hour)	Average difference between HV speed and Non-HV speed of speed of HV (km/hour)
00.00-05.00	1073	28	88	49	39
05.00-16.00	3264	73	93	71	22
16.00-21.00	4464	153	59	46	13
21.00-00.00	1889	35	112	60	52

In the evening time group, i.e 16.01-21.00, the road reach its peak as the average volume and average density are at the highest, i.e 4464 pcu/hour and 153 pcu/km, respectively. It caused to the decreased of the average speed of non-heavy vehicle to 59 km/hour and heavy vehicle to 46 km/hour. During this time, the space between vehicles are limited so the speed difference between two types of vehicles are narrow, even it was almost the same. After 21.00 to midnight, the density and traffic volume is decreased to 35 pcu/km and 1889 pcu/hour. It impacted the speed to be increased to 112 km/hour for non-heavy vehicle and 60 km/hour for heavy vehicle, where the speed difference is also widening.

From the description, we can see the correlation between traffic volume, density and speed of non-heavy and heavy vehicle. When the volume and density are low, vehicles have more space and the speed difference is bigger. As the volume and density increased, the speed is also increased until the road reach its maximum capacity then the speed start to decreased. The increased and decreased of volume and density impact to the speed difference between vehicles. This data in which the road has 3.5% gradient was compared to the other data which represents the traffic on 0% of road gradient [4]. It shows a significant difference on the speed gap between the two types of vehicles (HV and non HV) for both gradients, particularly at the lesser traffic density. As the maximum speed difference between heavy vehicle and non-heavy vehicle for 3.5% road gradient is 52 km/hour and the minimum is 13 km/hour, the maximum speed difference for 0% road gradient is 24.87 km/hour and the minimum is 8.32 km/hour. The difference between both gradients is almost 56% (for minimum) and 109% (for maximum). The speed difference between heavy vehicle and non-heavy vehicle on 3.5% gradient is 56%~109% higher than the one of 0%. This is due to heavy vehicle tend to slower its speed on steeper road while non-heavy vehicle do not make outstanding speed difference on steeper road.

3.2 Speed, density and volume relationships

Figure 3.1~3.3 show the distribution of 243 data regarding three traffic variables; density, speed and traffic volume. With regression techniques, it is found that the Exponential-model is the best model to represent the data of all the variables for 3.5% of road gradient. It can be seen on the trend line in Fig. 3.1~3.3. Correlation parameter between observation data and the regression model is shown in Table 2. Test using Pearson correlation coefficient show the three variable have a good correlation, which is between 0.753~0.893,

for the significance level of $\alpha=0.05$, and p -values less than 0.0001. It can be seen that the Exponential model represents the observation data well.

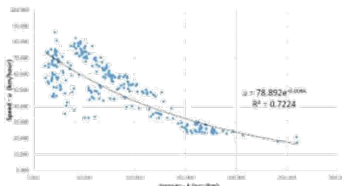


Fig. 3.1. Speed-Density Relationships

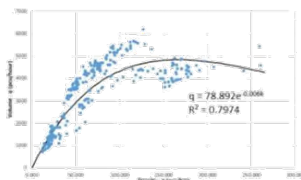


Fig. 3.2. Volume-Density Relationships

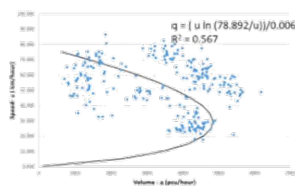


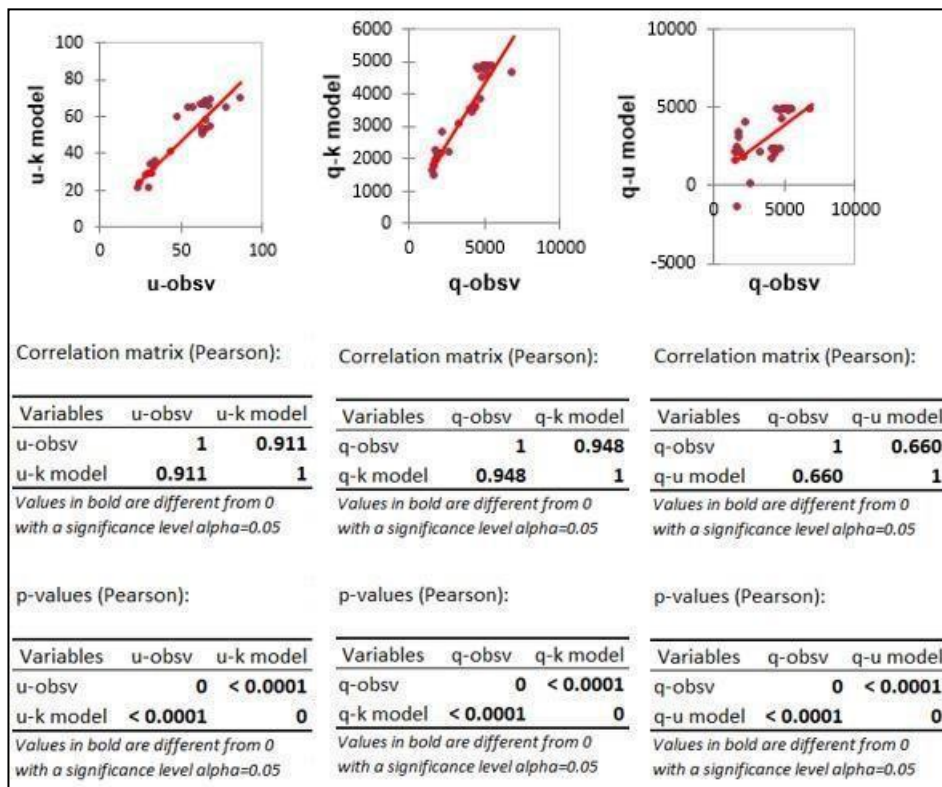
Fig. 3.3. Volume-Speed Relationships

Table 2. Correlation Test Result

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Furthermore, model validation is conducted using $\pm 20\%$ of the second 24-hour observation data (48 data). Using the Pearson correlation test, Table 3 shows that there is correlation between the observation data and model. Thus, it can be concluded that the model is valid to be used in this study.

Table 3. Correlation Parameters of Validation Test



3.3 Comparison with other road gradients

In accordance with the objective of this paper, the empirical traffic flow model of 3.5% gradient is compared to the other models that represent the other gradients of JORR. Fig 4.1~4.3 show the traffic flow diagrams of three different road gradients (i.e 0%, 2% and 3.5%) and table 4 shows their mathematical models. From Fig. 4.1, it can be seen that the speed performance of vehicle in 0% gradient is better than those in 2% and 3.5%. The speed difference of three different gradients is increasing with the increase of density. When the traffic density is very low, the speed difference between three states is quite big. However, along with the increase in density, the speed difference for the three states is closing to zero. As the density is 230 pcu/km, the speed of the road with gradient 3.5% is 19.85 km/hour; it is close to the speed of 2% gradient in which is 19.67 km/hour. It can be understood as vehicles have limited space so they are almost at the same speed.

Fig. 4.2 shows that along with the increase in density, the volume differences of three states are increasing. In very low density, the traffic volume is relatively the same for every gradient. Fig. 4.3 and Table 5 shows that the free flow speed (uf) for 0% gradient is the highest, followed by road with gradient 2%, and the lowest is road with gradient 3.5%. When being compared to the road with 0% gradient, the % of difference for the free flow speed is 9.3% for road with 2% gradient and 27.3% for 3.5% gradient. With data observed the actual capacity for the three gradients is the highest when in 0% gradient and decreasing as the road gradient is increasing. The % of difference between 0% gradient and 2% gradient is 9.3% and between 0% gradient and 3.5% gradient is 15.2%.

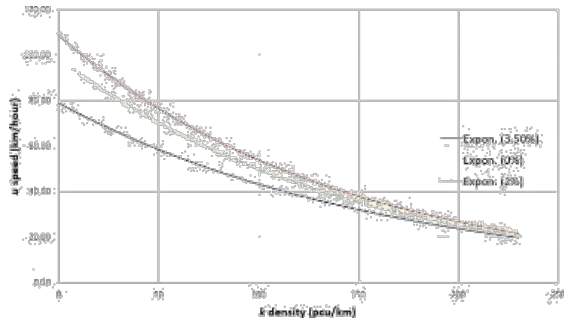


Fig. 4.1 Comparison of three gradient Speed-Density Relationships

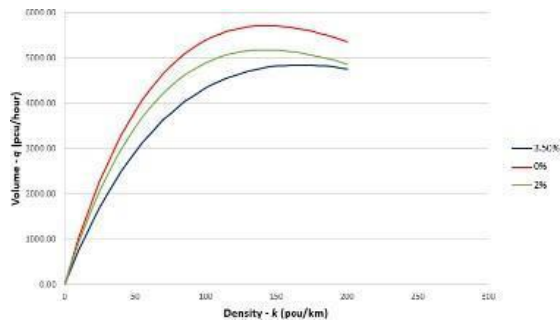


Fig. 4.2 Comparison of three gradient Volume-Density Relationships

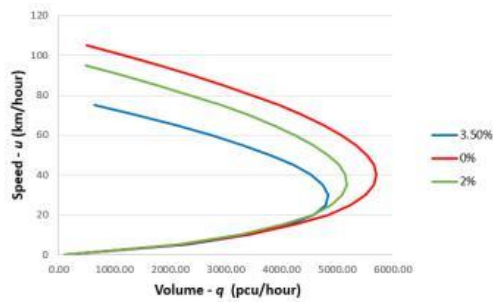


Fig. 4.3 Comparison of three gradient Speed-Volume

Table 4. Volume, Density and Speed Relationship

State	Speed-Density Relationship	Volume-Density Relationship	Volume - Speed Relationship
0%	$u = 108.49e^{-0.007k}$ ($R^2 = 0.9217$)	$q = 108.49k.e^{-0.007k}$ ($R^2 = 0.7814$)	($R^2 = 0.3102$)
2%	$u = 98.41e^{-0.007k}$ ($R^2 = 0.8298$)	$u = 98.41k.e^{-0.007k}$ ($R^2 = 0.8064$)	($R^2 = 0.4173$)
3.5%	$u = 78.892e^{-0.006k}$ ($R^2 = 0.7224$)	$u = 78.892k.e^{-0.006k}$ ($R^2 = 0.7974$)	($R^2 = 0.567$)

Note : u : speed (km/hour) ; k : density (pcu/km) ; q : volume (pcu/hour)

Table 5. Critical Measures of Traffic Flow Model

State	u_m (km/hour)	% of difference compared to 0% gradient	u_f (km/hour)	% of difference compared to 0% gradient	q_m (pcu/hour)	% of difference compared to 0% gradient	k_m (pcu/km)	% of difference compared to 0% gradient
0%	119	-	108.49	-	5701.59	-	142.857	-
2%	103	13%	98.41	9.3%	5171.28	9.3%	142.857	0%
3.5%	86	28%	78.892	27.3%	4836.88	15.2%	166.6	16.7%

Note : u_m, k_m : speed and density, respectively, at which the volume is maximum; q_m : actual capacity; u_f : free flow speed

4 Conclusions

Empirical study was conducted towards three different road gradients in the same toll system (JORR) to know the impact of the gradient to relationships of the three traffic variables; density, speed dan traffic volume. The results show that the speed difference between heavy vehicle and non-heavy vehicle on 3.5% gradient is 56%~109% higher than the one of 0%. This shows that in steeper road, heavy vehicle tend to reduce its speed more than non-heavy vehicles.

As the three gradients being compared, the speed performance for road with fewer gradients is better than the one that is steeper, for various traffic density levels. The actual capacity (q_m) difference between road with gradient 0% and 3.5% is 15.2% and the difference for the free flow speed (u_f) is 27.3%. Eventually, it can be concluded that road gradient significantly affects the traffic performance, especially for heavy vehicle, i.e. trucks.

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