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Applying Two-parameter Weibull Distribution to Model Stochastic Capacity of Arterial Roads During Peak Hours due to Changing Proportion of Heavy Vehicles

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Abstract Despite the increasing number of heavy vehicles (HVs) on the road, little attention is paid to the impact of HVs on traffic flow. Due to their different physical characteristics (length and size) and operational characteristics (acceleration and deceleration) compared to other vehicles, HVs have a physical and psychological impact on the traffic around them. On the other hand, many studies done on changes in road capacity yield a single value of road capacity. In this study, however, the road capacity is analyzed with probability distributions. This study found that the road capacity increases since HV reduction has a constant value with 85% and 50% cumulative probabilities. On major roads, reducing HV by 10%, 20%, 30% increases road capacity by 3-4%, 8% and 11-12% respectively. Lower HVs ratios are less likely to reduce road capacity. However, the speed of HV and other modes does not directly affect the cumulative probabilities. In addition, as the ratio of HV increases, the speed difference between vehicle types decreases. This study is limited to rush hour traffic flows so that a further study can consider the total duration of mixed traffic conditions.

Keywords Arterial Roads, Heavy Vehicles, Mixed Traffic, Stochastic Road Capacity

1. Introduction

The number of people and the number of goods moved are often used as measures of profitability. For example, an increase in the number of heavy vehicles (HVs) namely buses and trucks. In Bali, the number of buses and trucks increased by 6.5% (from 8,643 to 9,205) and by 5.66% (from 148,238 to 156,624) in the three years from 2018 to 2020 [1]. This increase in the number of vehicles indicates that the HV has increased the distance traveled on Bali's road network. However, a single value of road capacity does not reflect real-world observations, so capacity should be considered an inherently stochastic random variable. Road capacity is defined as the maximum number of vehicles that can pass a given point on a roadway during a given time period under prevailing roadway and traffic conditions [2,3]. Displaying capacity in this way requires identifying/ estimating capacity as a probability distribution over a range of values [2]. The cumulative distribution of the corresponding capacity values has come to be known as the 'capacity distribution function' and is considered a valuable tool for assessing road performance and efficiency. In addition, peak flow is considered an estimate of road capacity [2].

Numerous other studies have demonstrated that on-road passenger vehicles are often affected by the HVs, significantly altering their driving behavior such as headway, speed choice, and lane change decisions [4]. As such, HVs have a significant impact on mixed-traffic traffic, causing significant reductions in speed and traffic volume. Therefore, existing speed models for mixed traffic conditions underestimate the impact of HVs on traffic flow, and in some cases, simulation results can be far from the actual speed model. Such models could be significantly improved by accounting for HV effects.

Although the number of HVs is relatively small compared to other vehicles, the impact is quite noticeable, especially in areas with heavy traffic. Due to their different physical characteristics (length and size) and operational characteristics (acceleration and deceleration) compared to other vehicles, HVs have physical and psychological effects on surrounding traffic [4]. Despite the increasing number of heavy vehicle traffic [5], little attention has been paid to the impact of HVs on traffic flows. HVs consume more road capacity than passenger cars and have a greater impact on oncoming traffic. Measuring such differences is therefore of great importance for local governments and other authorities to address road design and congestion challenges [6].

Since HVs are longer than other vehicle types, the distance between vehicles is longer. HVs occupy more space on the road than passenger cars and have a greater impact on oncoming traffic [6]. The impedance that different types of his HVs pose to other vehicles in mixed traffic affects the overall capacity and level of service (LoS) of highways [7]. Furthermore, estimation of lane capacity in mixed traffic and lack of lane discipline by drivers create varying levels of difficulty [8]. Therefore, the effect of HV on traffic flow characteristics deserves more attention as it directly affects capacity [9].

The high rate of interaction between light vehicles (LV) and HVs and their significantly different speeds can create a mobility bottleneck [10]. This reduces the average speed and flow of all HVs on the road due to their operating characteristics. Understanding the deterrents induced by HV is important in traffic analysis as it affects not only traffic speed but also traffic flow and ultimately traffic capacity and LoS. To better understand the phenomenon of HV impact on capacity reduction, this study investigated mixed flow conditions on the arterial roads of Bali with and without median at varying numbers of lanes and speeds at peak hours. A previous study [11] also suggested that further research is needed on the influence of the presence of other transport modes on HV speed choice.

Previous studies [12-14] also stressed that the method of determining the capacity of roads in developed countries may not reflect traffic conditions in developing countries. Studies in developed countries do not consider the characteristics of mixed traffic flows, especially in Indonesia where motorcycles (MCs) dominate the traffic. For example, the distribution of speed data under homogeneous traffic conditions in developed countries follows a normal distribution, but not under heterogeneous/ mixed traffic conditions [12].

Technical guidance for determining the capacity of roads and intersections currently refers to the Indonesian Road Capacity Manual/MKJI [15]. However, given the high percentage of MC in Indonesia, including Bali Province, exceeding 85% [1], the MKJI method may need to be modified [16]. Therefore, in this study, we build another model besides analyzing the impact of HV on road capacity reduction using MKJI. Therefore, the two research goals are formulated as follows:

a. Determine the PCE values for arterial roads at different traffic levels, with an emphasis on traffic congestion. As a prelude to determining how the passenger car equivalence (PCE) factor changes and quantifying this change.
b. Analysis of the composition of vehicle heterogeneity (physical and operational characteristics of HV traffic) that impacts road capacity reduction.

If the relationship between HVs with reduced capacity can be identified, the appropriate action can be performed to prevent or minimize this reduction, depending on the level of HV penetration. Understanding the impact of HV traffic on reduced road capacity can help traffic management achieve travel times by preventing congestion. Jl. Denpasar-Gilimanuk and Jl. Gatot Subroto and Jl. Bypass Ida Bagus Mantra are examples of arterial roads in Bali frequently traversed by HVs, therefore performance from a traffic flow perspective can be improved through traffic management strategies. The scientific contribution of this study is to analyze the impact of HV traffic on road capacity reduction and to contribute to general knowledge of other variables that influence capacity reduction. The results of this study are expected to serve as a reference for formulating planning guidelines for the layout of cargo terminals around ports and airports. Transportation or distribution of goods can be performed by non-HV. It is specifically designed for the distribution of goods within the Province of Bali, but inter-island shipments can be routed via sea freight.

2. Materials and Methods

Data collection was performed using a video camera at three locations along the observation section, namely J1. Denpasar - Gilimanuk, Jl. Gatot Subroto Street and Jl. Bypass IB Mantra. The data collected include traffic volume (Q) and travel time (t) to determine speed (V) and road geometry conditions. Traffic volume and travel times for each segment are measured separately for each direction. The study area is the uninterrupted flow of traffic on straight and flat sections (0% grade) of the road. Also, the section should have no other access points near the data collection zone to have minimal or no lateral friction impact on traffic flow other than HV impact.

Collected traffic speed and volume data were extracted for each 5-minute aggregation. All vehicles are classified into three categories: MC, LV, and HV. Observation times are chosen during peak traffic hours, especially when it has a lot of traffic from 07:00 to 11:00 Bali local time chosen as the observation time. Based on the traffic data, the observed road segments refer to traffic flow conditions such as intensity (volume/ capacity ratio), traffic distribution, traffic composition, HV percentage, and presence/absence of side barriers (yes/no).

Table 1 shows the site traffic characteristics and road geometry conditions. Observations were made when the pandemic period began to subside, but traffic conditions were still lower than in non-pandemic conditions. However, previous observations indicated it was a peak hour from 07.00 – 11.00 am. Observations of a few side frictions (few pedestrians crossing the road, vehicles parked or stopped on the side of the road, unmanned vehicles passing by the side of the road, vehicles entering and exiting the land use) were measured along the 200-meter road section). MC has the largest percentage among the three observed modes, in the range of 61.11% and 81.31%, LV in the range of 16.41% and 30.68%, and HV in the range of 2.28% to 8.21%. This transport mode ratio indicates a mixed traffic flow condition. A previous study concluded that the lane width effect is more pronounced under mixed traffic conditions where vehicles do not follow each other [17]. A negative association was found between reduced capacity and the number of lanes, showing a downward trend from 16.33% for 2-lane highways to 8.85% for 5-lane highways [18].

Table 1. Traffic Composition and Road Geometry

Road Links	Coordinates (Easting, Northing)	Road Type	Median Width (m)
I	8°29'48.2";115°03'06.1"	2/2 UD	-
II	8°38'08.2";115°13'34.3"	4/2 UD	-
III	8°37'17.3";115°17'58.6"	4/2 D	5
	MC (units)	LV (units)	HV (Units)
I	4813 (61.11%)	2416 (30.68%)	647 (8.21%)
II	16148 81.31%)	3260 (16.41%)	453 (2.28%)
III	15981 74.19%)	4774 (22.17%)	78 (3.64%)
	Lane Width (m)	Road Width(m)	Shoulder Width (m)
I	3.20 /3.20	6.40	1.25 /1.25
II	6.00 /5.00	11.00	0.35 /0.70
III	3.35 /3.35	6.70	2.15 /1.30

Note:
MC = Motorcycle; LV = Light Vehicle; HV = Heavy Vehicle
Road Link I: JL. Denpasar - Gilimanuk
Road Link II: JL. Gatot Subroto Denpasar
Road Link III: JL. Bypass IB Mantra

3. Results and Discussion

3.1. Survey Results

Figures 1 to 4 show fluctuations in traffic volume and speed over the time of observation. The figure shows the fluctuations every hour with an interval of every five (5) minutes. The highest volume and speed values on the graphs are set at 5,500 vehicles/hour and 70 km/hour respectively to facilitate the analysis of the initial data for traffic volume and speed in all observed road segments.

Figure 1 shows the observed road segment on Jl. Denpasar-Gilimanuk (two-lane two-way undivided road). The volume and speed of MCs are higher than the two other modes (LVs and HVs). The highest MC volume is at 1,500 vehicles/hour and the average MC speed is below 50 km/hour. The traffic speed on Jl. Denpasar-Gilimanuk has the same pattern as that on Jl. Gatot Subroto (Figure 2), although the highest volume of MCs is close to 5,500 vehicles/hour.

The speed of HVs on Jl. Denpasar-Gilimanuk is slightly higher (average 35 km/hour) than that on Jl. Gatot Subroto (average 30 km/hour). The initial assumption was that a much higher volume of MCs on Jl. Gatot Subroto could reduce the speed of HVs. This is because the volume of LVs was not much different in these two road segments.

Table 2. Max and Min Values of Volume and Speed

Road Links	Volume (Vehicles/hour)					
	MC		LV		HV	
	Max	Min	Max	Min	Max	Min
I	1459	1035	677	566	199	132
II	5318	3254	883	771	131	88
III	1601	997	809	381	141	98
IV	4262	1750	732	386	92	57
	Speed (km/hour)					
Road Links	MC		LV		HV	
	Max	Min	Max	Min	Max	Min
I	47	45	44	41	37	34
II	44	42	36	34	30	28
III	53	52	55	53	46	43
IV	60	59	59	57	30	29

Note:
MC = Motorcycle; LV = Light Vehicle; HV = Heavy Vehicle
Road Link I : JL Denpasar - Gilimanuk (2 ways)
Road Link II : JL Gatot Subroto (2 Ways)
Road Link III: JL Bypass IB Mantra (Eastbound)
Road Link IV: JL Bypass IB Mantra (Westbound)

Meanwhile, the traffic volume and speed data on Jl. Bypass IB Mantra are shown separately per direction because with the presence of median, speed is not to be affected by traffic from the opposite direction. For the road segments that do not have a median, however, traffic volume and speed data are combined, because speed is affected by traffic from the opposite direction. Traffic data are observed every 5 minutes to accommodate variations in flow and speed due to the heterogeneous nature of traffic.

Table 2 shows that MCs have the highest volume in all road segments, in particular Jl. Gatot Subroto (two ways) and Jl. Bypass IB Mantra (westbound). The same pattern also occurs for speed but in the observation segment of Jl. IB Mantra (eastbound), where the maximum speed is on LVs.

3.2. Passenger Car Equivalent (PCE)

Table 3 shows the determination of PCE from three (3) types of vehicles. The value of pce is determined from traffic speed data at five-minute intervals to convert heterogeneous into homogeneous traffic flows. The mean value of PCE is determined from the Dynamic Car Unit (DCU) equation [17].

$$DEF_c = \frac{V_{mc} / V_i}{A_{mc} / A_i} \quad (1)$$

where,

DEF_c: Dynamic equivalent factor value for type i of a mode of transport

V_{mc}: The mean speed of light vehicles as reference (km/h)

V_i: The mean speed of type i of a vehicle (km/h)

A_{mc}: The area (length x width) of a light vehicle as a reference (m^2)

A_i: The Area (length x width) of type i of a vehicle on the road (m^2)

There has been a large variation in the estimated value of pce especially for HVs because of the difference in the average speed of HVs in all observation segments. Speed choice by HVs can be influenced by the volume and speed of MCs and LVs, the driving behavior of vehicle drivers, and geometric and road pavement conditions.

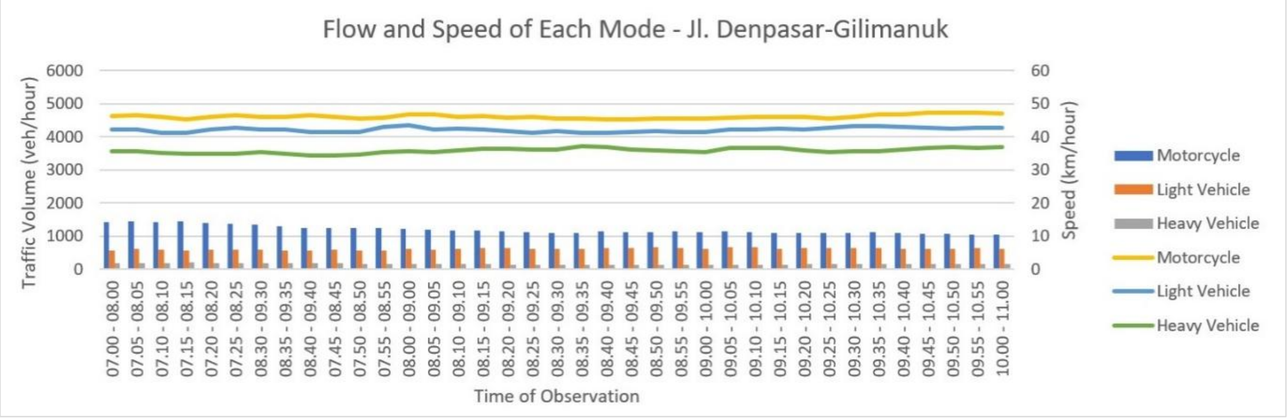

Figure 1. Volume and Speed on JL Denpasar-Gilimanuk

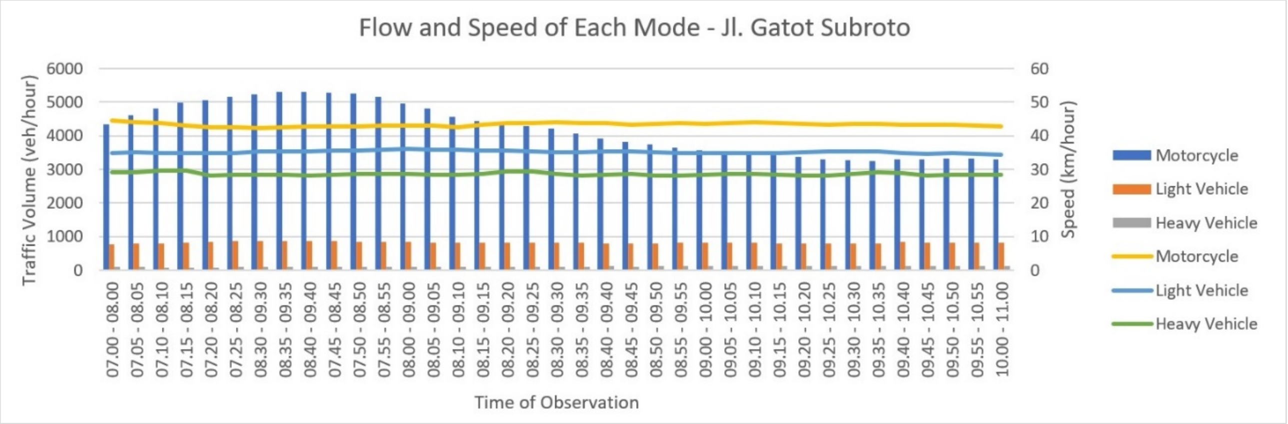

Figure 2. Volume and Speed on JL Gatot Subroto

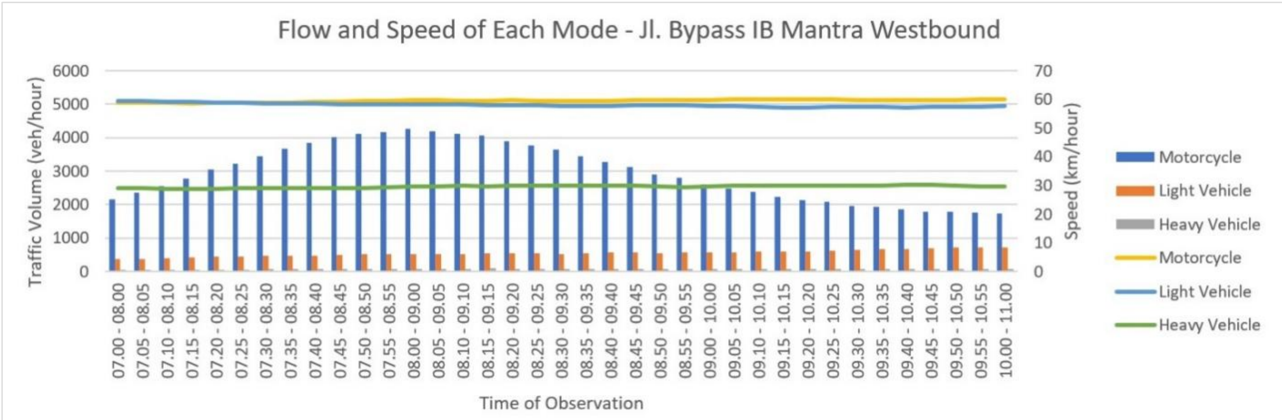

Figure 3. Volume and Speed on JL Bypass IB Mantra Westbound

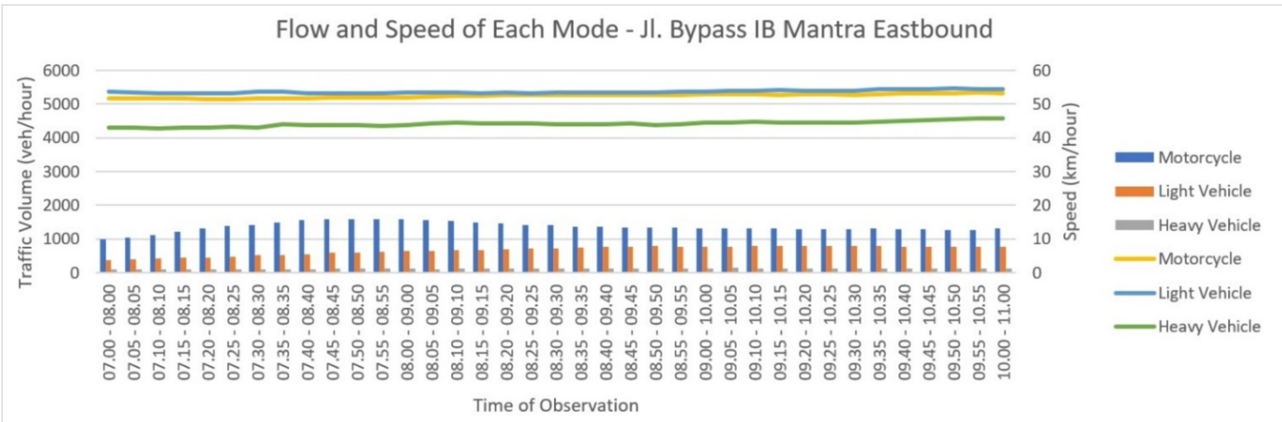

Figure 4. Volume and Speed on JL Bypass IB Mantra Eastbound

The results of a previous study in Korea [19] showed that in addition to the average speed, the speed deviation between vehicle types decreased with the increase in the proportion of HVs. In other words, in traffic groups that make up the same platoon, each vehicle is forced to have the same speed which results in a homogeneous speed. This indicates that the presence of HVs can reduce the possibility of conflicts between vehicles in the traffic flow.

PCE in Table 3 is a conversion factor from heterogeneous traffic volume data into homogeneous ones, namely into Passenger Car Units (PCU). Figure 5 shows the proportion of each type of vehicle in units of PCU/hour. It can be seen that the proportion of vehicle types has differences when expressed in units between vehicles/hour and PCU/hour. This difference is significantly influenced by the pce value used. For example, the PCE for HVs in Table 3 has a large value, so the proportion of HVs seems to increase in units of PCU/hour. As a result, in PCU, the proportion of MCs is no more than 30% while the proportion of HVs reaches 40%, especially on Jl. Denpasar-Gilimanuk. However, in reality, the volume of MCs per vehicle unit can be more than 80%.

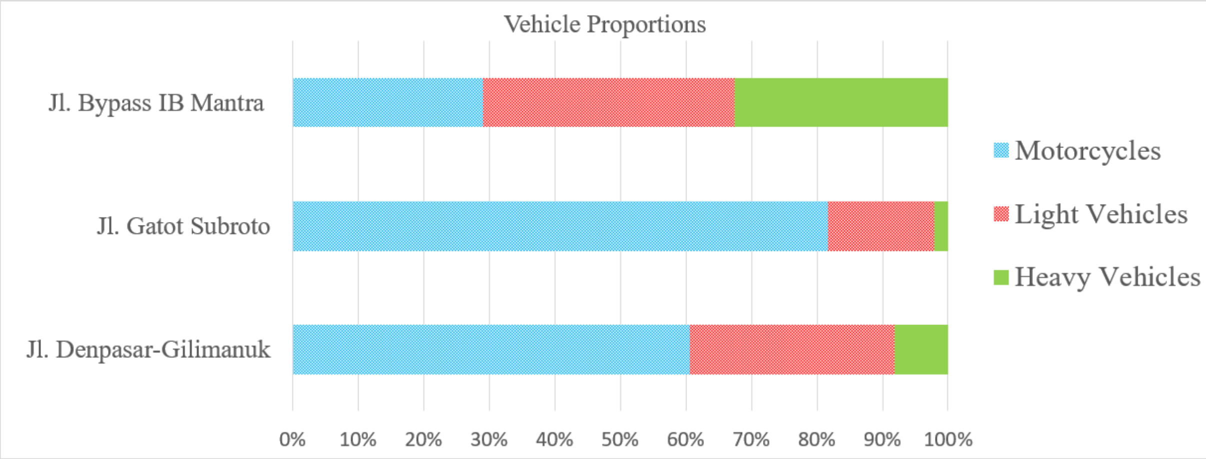

Figure 5. The proportion of Each Mode

Table 3. Passenger Car Equivalent (PCE)

Road Links	**V_{MC} (km/h)**	**V_{LV} (km/h)**	**V_{HV} (km/h)**
I	42	46	12.18
II	35	43	12.18
III	58	60	12.18
IV	54	52	12.18
Road Links	A_{MC} (m^2)	A_{LV} (m^2)	A_{HV} (m^2)
I	1.2	12.18	31.46
II	1.2	12.18	31.46
III	1.2	12.18	31.46
IV	1.2	12.18	31.46
Road Links		Average PCE Values	
	MC	LV	HV
I	0.09	1	3.01
II	0.08	1	3.12
III	0.10	1	4.99
IV	0.10	1	3.17

Note:

MC = Motorcycle; LV = Light Vehicle; HV = Heavy Vehicle

Road Link I : JL Denpasar - Gilimanuk

Road Link II : JL Gatot Subroto Denpasar

Road Link III: JL Bypass IB Mantra (Westbound)

Road Link IV: JL Bypass IB Mantra (Eastbound)

Normally, PCE depends on many factors comprising congestion level and traffic composition. The proportion of HVs in the traffic stream is not either monotonic or linear. The results in Table 3 are consistent with the assumption from a past study that the PCE value is considered insensitive to the level of HVs presence in both undersaturated and saturated traffic conditions [6]. It is likely that as the level of congestion increases, the presence of HVs becomes more obvious and interrupts traffic flow when compared to the absence of HVs. Therefore, it is likely that PCE value would increase.

PCE factor is commonly used to assess differences between large HVs and passenger cars in terms of road capacity and congestion analysis. PCE factor measures the magnitude of large vehicles' effect on the following traffic compared to passenger cars. In other words, PCE factors have a significant impact on road capacity and LoS [6].

The purpose of this study is to analyze the impact of changes in the percentage of HVs on the probability of road capacity reduction. So the proportion of vehicles inhomogeneous traffic situations is used with units of PCU/hour. The capacity is the limit where below the limit value, the traffic volume is still operating and above the limit value, the traffic volume breaks down into stop-and-go traffic. Capacity in this sense is by no means a constant value. In several previous studies [20,21], empirical analysis of traffic flow patterns calculated at 5-minute intervals, clearly shows that the capacity of the Weibull distributed road segment with almost constant shape parameters, which represents the value of the variance.

3.3. Road Capacity Distribution

The mathematical type of road capacity distribution function is studied by referring to a past study [2] as follows:

$$F(x) = 1 - (\exp. -((\frac{x}{\beta}))^{\alpha}) \text{ for x} \gg 0 \quad (2)$$

Where

α : shape parameter

β : scale parameter

For parameter estimation of the distribution function, the maximum likelihood method, the probability function, or the natural logarithm (log-likelihood) is maximized to calibrate the distribution function. Figures 6 - 9 show the probability of the arterial road capacity if there is a change in the percentage of the number of HVs in the traffic flow. The probability is determined based on the parameters of the Weibull distribution function. The summary of the decrease in probability is shown in Table 4. Based on the standard deviation of the traffic volume shown in the table, the traffic volume on Jl. Bypass IB Mantra, both eastbound and westbound have a higher variation than that on Jl. Gilimanuk and Gatot Subroto. This can cause a large difference in the shape parameter of the Weibull distribution value on Jl. Bypass IB Mantra compared to that on Jl. Denpasar-Gilimanuk and Jl. Gatot Subroto.

The shape parameters in the Weibull distribution range from 8 to 30. The Denpasar-Gilimanuk and Gatot Subroto roads are arterial roads without a median, i.e 2 lane-2 way undivided road, have almost the same shape parameter values, which are between 28-30. Meanwhile, the IB Mantra Bypass road is an arterial road of type 4-lane 2-way divided road. For roads with a median, the speed in each direction has no influence on that in the opposite direction. The shape parameter values are almost the same, 8 and 11 for the eastbound and westbound traffic respectively. This is probably because the traffic volume (including the volume of HVs) in eastbound traffic is much smaller than that of westbound traffic. For a 5-minute observation, the road capacity is in the range of 1.00-1.02 times the capacity for an hour. This is in line with a past study by Lu, et al (2020) that concluded HVs use more road space than LVs and MCs and have a greater effect on traffic flow. Similarly, a past study [7] found that the impedance caused by different HVs to other vehicles in mixed traffic flows affects the overall road capacity and LoS.

Table 4. Weibull Distribution Parameters

Road Links	**Shape Parameter α**		
	10%	20%	30%
I	28	29	30
II	30	29	28
III	11	11	11
IV	8	8	8
	Scale Parameter β (PCU/hour)		
	10%	20%	30%
I	1182	1131	1081
II	1503	1469	1434
III	1245	1205	1165
IV	1228	1188	1148
	σ standard deviation (PCU/hour)		
	10%	20%	30%
I	44	39	34
II	50	52	55
III	122	118	114
IV	174	170	166

Note:

Road Link I : JL Denpasar - Gilimanuk

Road Link II : JL Gatot Subroto Denpasar

Road Link III : JL Bypass IB Mantra (Wetbound)

Road Link IV : JL Bypass IB Mantra (Eastbound

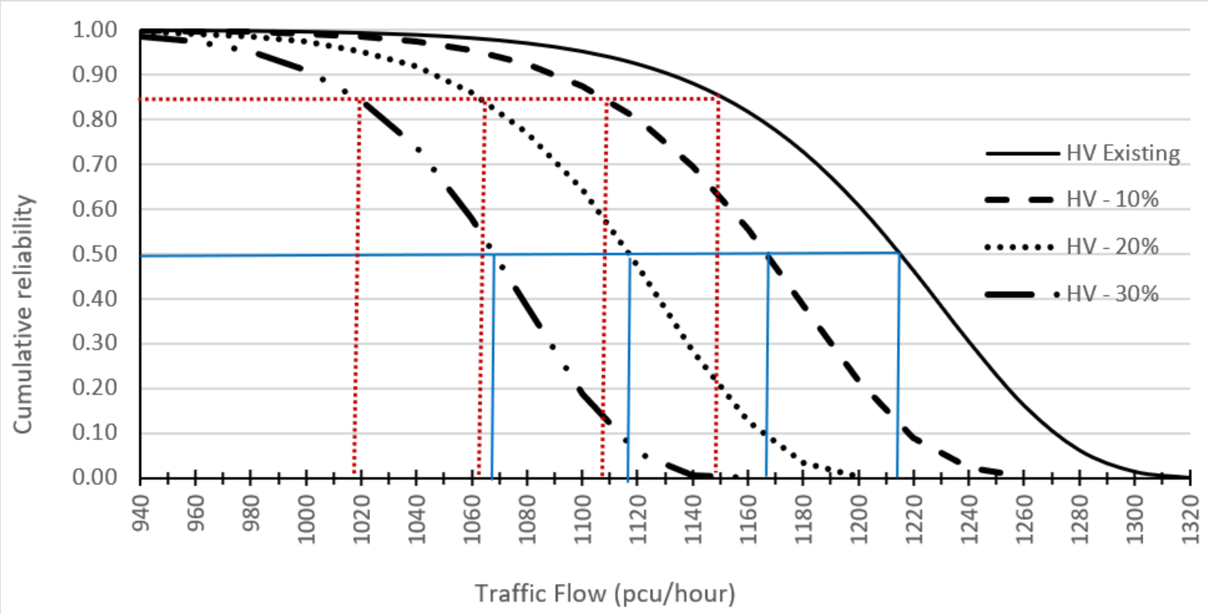

Figure 6. Weibull Distribution-Probability of Increased Road Capacity due to Decrease in Percentage of HVs on Jl. Denpasar-Gilimanuk

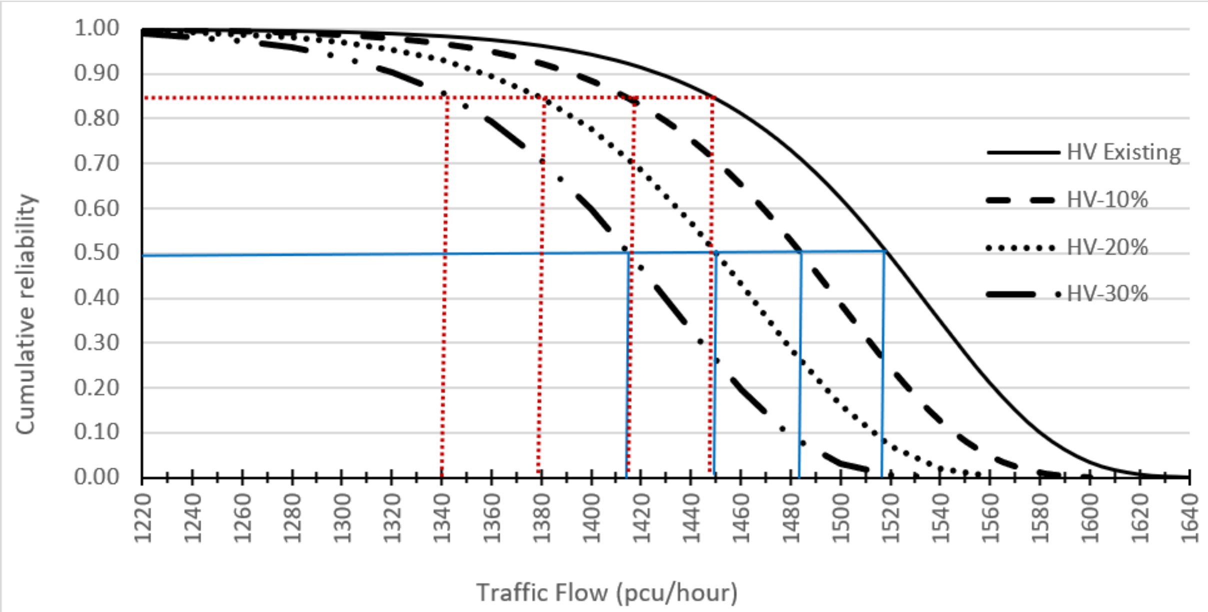

Figure 7. Weibull Distribution-Probability of Increased Road Capacity due to Decrease in Percentage of HVs on Jl. Gatot Subroto

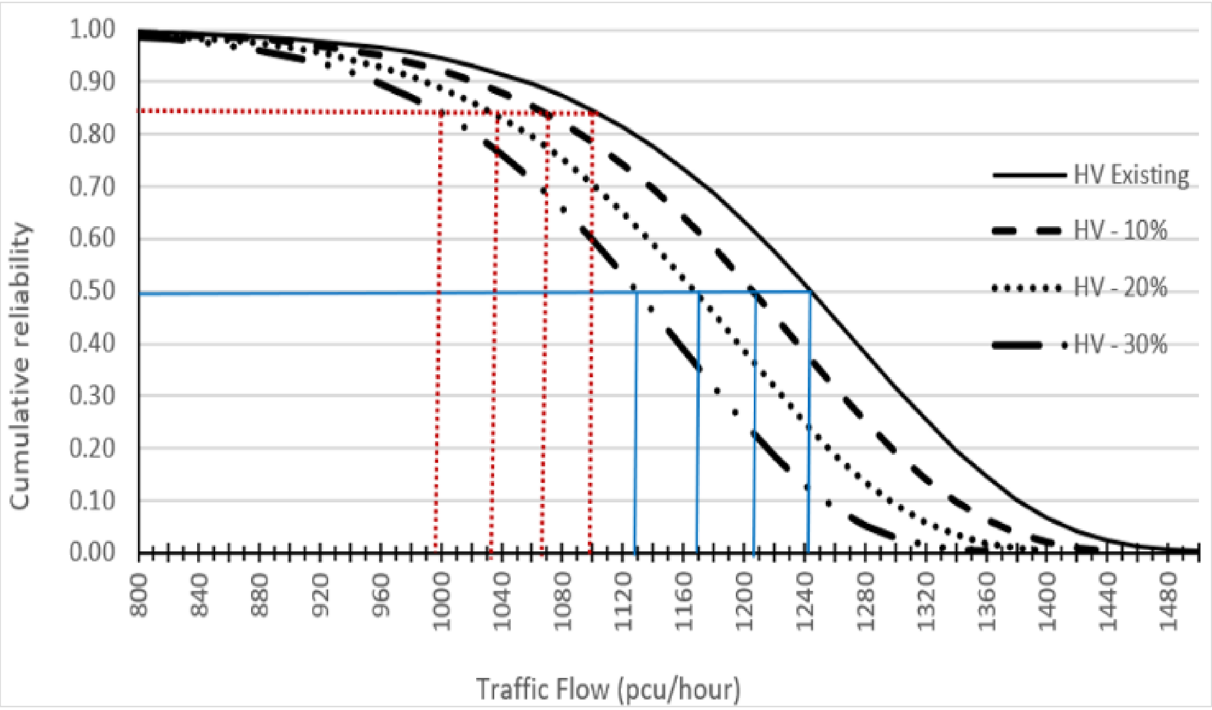

Figure 8. Weibull Distribution-Probability of Increased Road Capacity due to Decrease in Percentage of HVs on Jl. Bypass IB Mantra Westbound

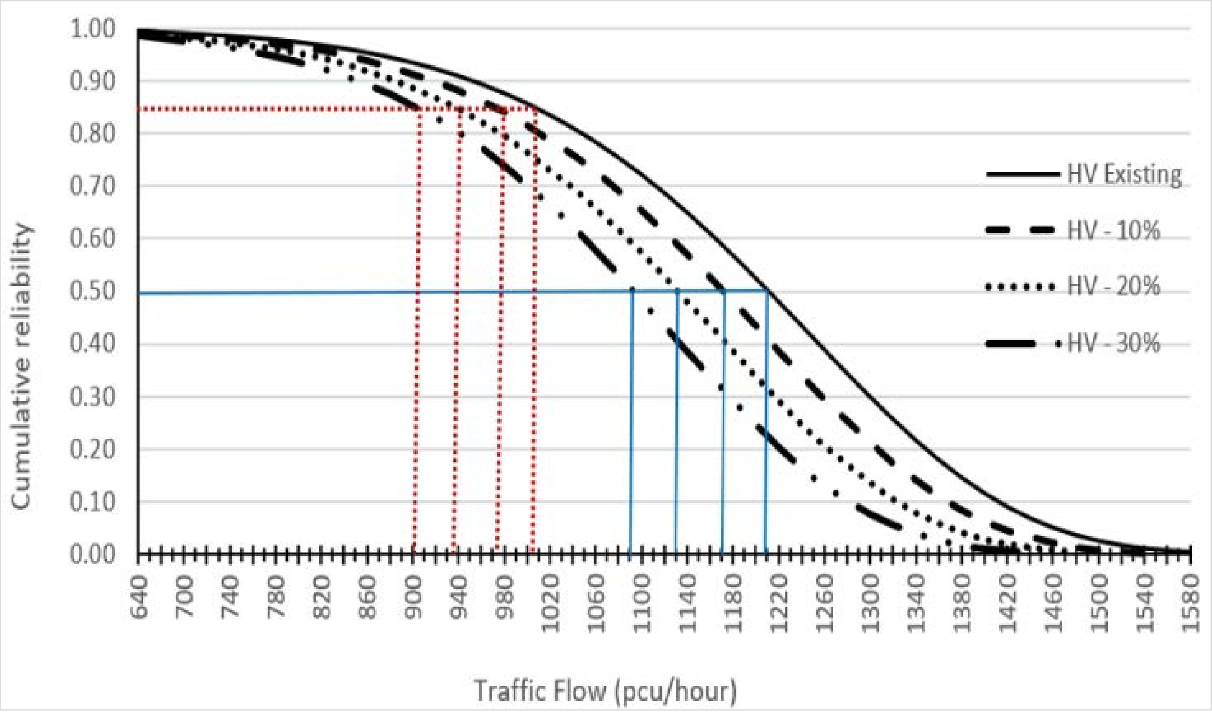

Figure 9. Weibull Distribution-Probability of Increased Road Capacity due to Decrease in Percentage of HVs on Jl. Bypass IB Mantra Eastbound

The increase in road capacity due to the decrease in HVs at the cumulative probability of 85% and 50% in Table 5 shows a constant value. This indicates that the reduction in the percentage of HVs on all observed road segments can be generalized according to each value in Table 5. For example, on Jl. Denpasar-Gilimanuk, a 10% reduction of HVs will increase the road capacity between 3%-4%., a 20% reduction of HVs will increase 8% of the road segment capacity and a 30% reduction of HVs will increase 11-12% of road segment capacity.

Table 5. Probability of the Increasing Road Capacity Due to Decreasing Proportion of HVs

Road Links	**85% Cumulative Reliability**		
	HV-10%	HV-20%	HV-30%
I	3%	8%	11%
II	2%	5%	8%
III	3%	6%	10%
IV	3%	7%	10%
Road Links	50% Cumulative Reliability (Median Value)		
	HV-10%	HV-20%	HV-30%
I	4%	8%	12%
II	2%	5%	7%
III	3%	6%	9%
IV	3%	7%	10%

Note:

HV = Heavy Vehicle

Road Link I : JL Denpasar - Gilimanuk

Road Link II : JL Gatot Subroto Denpasar

Road Link III: JL Bypass IB Mantra (Westbound)

Road Link IV: JL Bypass IB Mantra (Eastbound)

Among the observed roads, the smallest probability of increasing capacity is on Jl. Gatot Subroto, this can be due to the smaller proportion of HVs in this segment compared to the other three sections. In mixed traffic conditions, the estimation of road capacity poses different levels of difficulty with flow and lane discipline [8]. Therefore, the influence of HVs on traffic flow characteristics requires greater attention because of its direct effect on road capacity [9].

The influence of the speed of HVs and other modes has an indirect effect on determining the cumulative probability. This is because speed is only used when determining the PCE value. This is consistent with a past study [10] which summarized that the high percentage of interactions between LVs, MCs, and HVs, each of which has a significant speed difference, can cause moving congestion. As a result, the average speed of HVs on the road is reduced due to their operational characteristics.

The analysis shows that the impact of HVs is imperative as it influences traffic speed, traffic flow, and, eventually road traffic capacity. This study focuses only to analyze the mixed traffic conditions during peak hours. A further study, therefore, is required to consider the overall period of mixed traffic flow conditions.

4. Conclusions

Despite their smaller percentage in the traffic stream, HVs are known to cause significant impacts on traffic flow and road capacity. A single road capacity value, however, does not reflect real mixed traffic conditions in developing countries, so the capacity should be considered an inherently stochastic random variable. To do this, the capacity must be determined and estimated as a probability distribution over a range of values. The cumulative distribution of the corresponding capacity values is referred to as the "capacity distribution function" and considers a valuable tool in evaluating the performance and efficiency of arterial roads.

This study found that between 10% and 30% reduction of HVs will increase the arterial road capacity by between 3% and 12%. Despite traffic heterogeneity and smaller portions of vehicles, HVs have direct and significant influences on arterial road capacity. As the ratio of HV increases, however, the speed difference between vehicle types decreases. The speed of HVs and other modes concluded to have an indirect effect on arterial road capacity.

This study was used only for the peak hours of traffic flow conditions. A further study, therefore, needs to be conducted considering the overall period of traffic flow conditions so that capacity reduction due to HVs can be captured comprehensively.

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