# THE PASSENGER CAR UNIT VALUES OF MOTORCYCLES AT THE BEGINNING OF A GREEN PERIOD AND IN A SATURATION FLOW

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## ABSTRACT

The aim of this study is to estimate the Passenger Car Unit (PCU) values of motorcycles in two traffic environments: at the beginning of a green period and in a saturation flow. Motorcycles are able to undertake both lane-based and non-lane-based movements in mixed traffic. Hence their PCU values cannot be adequately measured simply by their headways. In addition, their PCUs could vary according to the traffic context of urban networks, which makes their PCU estimation even more complex. This study employed the flow rate method to estimate motorcycle PCU values, with the help of a recently developed agent-based simulation model, which is capable of representing the characteristic movement patterns of motorcyclists. An experiment was designed to conduct a systematic analysis, in which four conditioning variables were considered: the advanced stop line, the number of lanes, the width of lanes and the proportion of motorcycles. The simulation results showed that at the beginning of green periods, the key factor affecting the PCU values was the number of motorcycles able to filter to the head of the queue. However, in saturation flow, the key factor was the opportunity for motorcycles to move alongside another vehicle in the same lane. An ex-post analysis was conducted using a regression model to fit the simulation results. This model indicated that the PCU values of motorcycles at the beginning of green periods are averagely 0.237 lower than those in multiple-lane saturation flows. In addition, the PCU values decrease 0.143 with every 1.0 m increase of the lane width. PCU values for motorcycles in different traffic conditions are suggested using this model.
*Keywords: PCU, PCE, Motorcycle, Mixed traffic, Microsimulation model, Road capacity*

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# INTRODUCTION

The flow rate of homogeneous passenger car traffic can be expressed in terms of vehicles per lane per hour. In mixed traffic, this expression is not appropriate as different vehicle types cause different disturbances to the traffic. Hence, the concept of Passenger Car Unit (PCU) or Passenger Car Equivalent (PCE) is used to convert the vehicle counts in mixed traffic to an equivalent passenger car flow.

The PCU value of a passenger car is defined to be 1.0. Each vehicle type is assigned a single PCU equivalent to represent its relative disturbance to the flow under the prevailing traffic condition. Sometimes a set of PCU values is assigned to a vehicle type to represent the various disturbances its presence invokes in different traffic environments. For example, the disturbances that motorcycles cause to the flow could vary with the factors such as the movements at intersections, the flow conditions, the frequency of moving between formal lanes and the layout of the section of the road system. Hence, its PCU value would vary with each traffic environment and its behaviour within that environment.

There are currently a wide range of PCUs for motorcycles found in the literature (Wigan, 2000). For example, the value can be as low as 0 (Powell, 2000), or as high as 1 (Road Research Laboratory, 1965). Without a systematic analysis and careful contextual qualifications on the applicability of each value, such a wide range of PCUs from different sources causes confusion. Such confusion can also lead to significant errors when estimating the capacity of roadways. Hence, for mixed traffic management, it is crucial to have a better understanding of the PCU values (subsequently referred to simply as ‘PCUs’) for motorcycles under various traffic conditions. As a specific range of PCU values could only be valid for some specific traffic conditions in some specific areas, the geographical scope of this study has been carefully defined. The scope of this study focuses on the flows affected by stop lines in urban networks at Central London to investigate the PCU values of motorcycles at the beginning of green periods and in saturation flows.

It can be difficult to estimate the PCU values for motorcycles by conducting an investigation in the real world as many conditioning variables have to be carefully controlled under different scenarios. To reduce this complexity to a manageable form, a simulator capable of describing the characteristic behaviour patterns of motorcycles and their interactions to different surrounding environments (Lee et al., 2009) is selected to carry out this analysis. This simulator is able to investigate how motorcycles utilise various forms of road space based on different driving conditions. In this simulator, variables related to PCUs such as the number of lanes, the width of lanes, the installation of advanced stop lines, the proportion of motorcycles and the congestion levels can be manipulated. Hence, it is an ideal tool for this study, although there might still be other variables of interest to some which are not catered for in the model.

This paper is organised as follows: Section 2 reviews the PCU values in the literature and decides the method for this study. Section 3 describes the methodology. Section 4 presents the simulation results and an ex-post linear regression analysis. Section 5 draws several conclusions for this paper and points out the possible directions for future work.

# LITERATURE REVIEW

A wide range of motorcycle PCUs can be found in the literature (see Table 1). As the way that motorcycles utilise road space varies with the traffic environment, their PCU values might not be 'portable', i.e., a single PCU value could not be used in different traffic environments or in different areas. Significant errors might be caused when specific PCU values are not used appropriately. This issue can be more critical for those areas having large number of motorcycles. A systematic analysis of motorcycles' PCUs in different traffic environments and different areas is therefore necessary.

Table 1 PCUs of motorcycles in the literature

| Source | PCU | Note |
|---|---|---|
| The 'best available value in the literature' | 0.5 | • Generally derived from road occupancy, or as a plausible value in the absence of hard data |
| Quoted in Wigan (2000) | 0.2 | • Quoted from the Indonesian Highway Capacity Manual, for congested signalised intersections |
| | 0.25 | • Quoted from the Indonesian Highway Capacity Manual, for free running urban road sections |
| Chandra and Kumar (2003) | 0.25 ~ 0.31 | • Measured in road sections |
| Highway Department of Bangladesh (2006) | 0.75 | • Used in Bangladesh |
| Branston and Zuylen (1978) | -0.08 | • Measured from saturation flows at intersections by using the headway ratio method |
| | 0.04 | • Measured from saturation flows at intersections by using the flow rate method |
| Quoted in Powell (2000) | 0 | • During the first 6 sec of a green period at a signalised intersection, quoted from May and Montgomery (1986). |
| | 0.53 ~ 0.65 | • After the 6th sec of a green period at a signalised intersection, quoted from May and Montgomery (1986). |
| Turner and Harahap (1993) | 0.37 | • Measured from saturation flows at intersections by using the headway ratio method |
| Hossain (2001) | 0.15 ~ 0.30 | • Measured from saturation flows at intersections by using the flow rate method |
| Quoted in Nguyen and Montgomery (2006) | 0.25 | • Used in Vietnam. Nguyen and Montgomery (2006) used it for calculating saturation flow rates in signalised intersections. |
| Kimber et al. (1982) | 0.4 | • Used in most studies since early 1980s in the UK |
| Lan and Chang (2005) | 0.17 ~ 0.49 | • Measured by using Cellular Automata Modelling under different speeds, proportions of motorcycles and lane widths |
| Road Research Laboratory (1965) | 1.0 | • For rural roads; used in most studies in 1960s and 1970s in the UK |
| | 0.75 | • For urban streets and roundabouts; used in most studies in 1960s and 1970s in the UK |
| | 0.33 | • For signalised intersections; used in most studies in 1960s and 1970s in the UK |

The types, sizes of powered two wheelers covered by the term ‘motorcycle’ in these studies vary substantially. This factor has not been addressed in the present work. Among the methods for estimating PCU values, both flow rate methods (Branston and van Zuylen, 1978; Hossain, 2001; Demarchi and Setti, 2003; Nguyen and Montgomery, 2006; Sumner et al., 1984) and headway methods (Branston, 1977) are widely used and the latter may be argued to have a sounder theoretical basis. However, both types of methods have their pros and cons. The main limitation of the flow rate methods is that the PCUs have to be measured in a saturation flow or in a congested flow. Otherwise, this type of method will simply link the low flow volume to the disturbance of non-passenger cars. The disadvantage of the headway ratio method is that it can only estimate the PCUs of vehicles which strictly follow the lane discipline rules. The PCU equivalent of a vehicle type with less precise lane discipline cannot be estimated due to its inconsistent headways. A summary of the methods for estimating motorcycles’ PCU values can be found in Lee et al. (2010).
The flow rate method is adopted in this study to estimate the PCUs of motorcycles as the headway ratio method cannot really handle vehicles with loose lane discipline. The value of the flow rate method in this study is that it calculates PCU values using the difference of the flow rates caused by the presence of a certain vehicle type. As all the potential disturbances caused by motorcycles’ lane based as well as non-lane-based movement patterns will be reflected in the flow rates, the impact of motorcycles can be captured and converted to PCU equivalents.

# METHODOLOGY

The flow rate method was adopted in this study to estimate the PCUs of motorcycles. The flow volumes for calculating the PCUs were obtained by using a microscopic traffic simulation model. Two types of traffic environments, the beginning of a green period and the saturation flow, were investigated. This section details the traffic simulation model and the design of experiments.

## Methods for estimating PCUs at the beginning of a green period

The PCUs of motorcycles at the beginning of a green period were estimated by counting the vehicles passing the traffic signal in the simulator. The beginning of a green period refers to the time span beginning at the instant when the green light shows and lasting a few seconds before the flow rate reaches saturated (see Figure 1). In this period the motorcycle is believed to have a low PCU value (May and Montgomery, 1986; Powell, 2000), and is the region where the substantially larger acceleration potential of motorcycles of all sizes over other vehicles would be expected to make a positive difference.

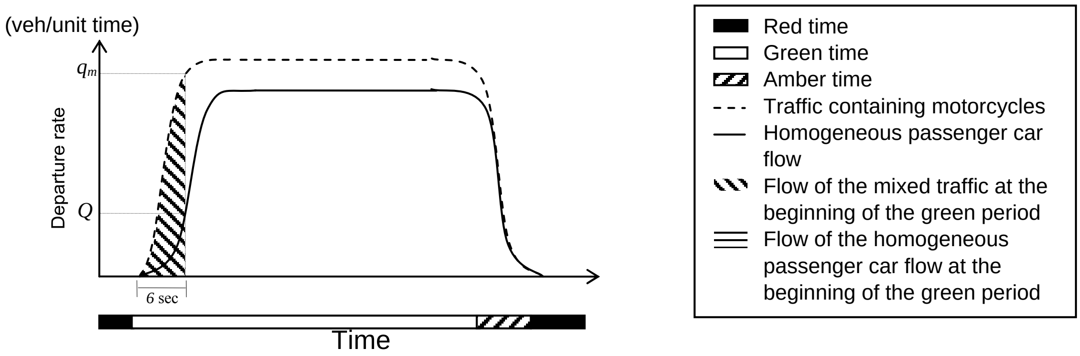


Figure 1 The flow rates during a green period from a saturated approach

In order to present the benefits of installing a motorcycle reservoir, this study defined the time span of the beginning of a green period as 6 sec as the simulator showed that most motorcycles kept in the motorcycle reservoir during the red period were able to pass the stop line in the first 6 sec of a green period. Motorcycles' PCUs were estimated by the flow rate method, the equation of which is shown below:

$$pcu_i = \frac{1}{p_i}\left(\frac{Q}{q_m} - 1\right) + 1 \qquad (1)$$

where $pcu_i$ : the PCU value of vehicle type $i$,
$Q$ :the saturation flow rate,
$q_m$ : the mixed flow rate, and
$p_i$ : the proportion of vehicle type $i$ in the mixed traffic.

## Methods for estimating PCUs in saturation flow

The PCUs of motorcycles in saturation flow were estimated by counting the vehicles passing the traffic signal in the simulator when the flow rate is saturated. This flow rate refers to the departure rate at the central plateau region of Figure 1. The interval selected for collecting the vehicle counts was between the 37th and 48th seconds of the green time. This setting ensured that the flow volumes had reached the stable plateau area. Equation (1) was then employed to estimate motorcycles' PCUs.

## The Simulator and the simulation environment

Currently most traffic simulation software packages have not provided for any non-lane-based movements of bicycles or motorcycles (e.g. Paramics Microsimulation, 2008; PTV, 2007). This study chooses a validated simulator, Bikesim (Lee et al., 2008; Lee et al., 2009), which features its capability of representing the motorcyclists' characteristic movements, to carry out the investigation.

Bikesim is an agent-based computer simulation model developed based on the concept of dynamic virtual lane-based movements of motorcycles. In Bikesim the movements of motorcycles are described by several behaviour patterns such as the vehicle-following behaviour, the gap acceptance behaviour and the path choice behaviour. These behaviour patterns are expressed by several mathematical models which are calibrated by using video data collected at Victoria Embankment in Central London, containing information on the trajectories of 2,109 vehicles including 477 motorcycles. Motorcycles in Bikesim are simulated in a two-dimensional manner. The minimum spatial and time units are 0.01 m and 0.1 sec respectively to capture their delicate filtering and overtaking behaviour. As Bikesim is able to represent motorcycles' behaviour patterns realistically and is well-calibrated, it is an appropriate tool for this research.
The simulation environment in this simulator was a one-way link with a speed limit of 50 km/hr, as shown in Figure 2. This link consisted of several lanes with a traffic signal at the end. The number and the widths of these lanes varied according to the settings of the simulation scenarios. An advanced stop line was set 5 m upstream from the traffic signal to investigate the effects of a motorcycle reservoir on the flow capacity during the early green period.

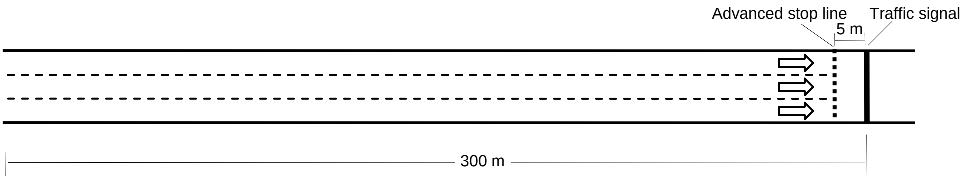


Figure 2 The schematic diagram of the simulation environment

## Design of the experiment

The PCUs were estimated by counting the vehicles passing the traffic signal in the simulator (see Figure 2). The length of the link was set to be 300 m long, which allowed motorcycles generated from the upstream end of this link to mix with other vehicles. The cycle of the traffic signal was set to be 150 sec green and 150 sec red. Such a long red period ensured that a certain amount of traffic was queuing upstream from the stop line and a saturation flow would occur in the green time. In addition, the filtering behaviour of motorcycles in a queue and their movements when seeking to approach the head of the queue were simulated. 100 signal cycles were simulated over a simulated period of 30,000 sec. Four of the possible available variable factors that could affect road capacity were manipulated or controlled in the experiment, described below:

1. Lane width: It is assumed that a wide lane will facilitate the filtering behaviour of motorcycles in a slow-moving traffic or in a queue. In congested urban networks, such filtering behaviour offers motorcycles some advantage over passenger cars in terms of speed and would affect their PCUs. In addition, Burge et al. (2007) found that the ability to filter is a significant factor in motorcycle ownership and commuter

usage. Hence, four levels of lane widths were set in this study, 2.0m, 2.5m, 3.0m and 3.5m to investigate their effects.

2. Number of lanes: It is assumed that a road with more lanes will offer motorcycles more opportunities and freedom to drift between lanes, overtake and exhibit the filtering behaviour. Robertson (2002a) found that the filtering behaviour usually happened between lanes rather than between the kerb and the side of the roadway. Thus, a multi-lane road could provide more opportunities for filtering. The traffic flows with one lane, two lanes and three lanes were simulated in this study (Robertson, 2002).

3. Proportion of motorcycles: Motorcycles are able to use the road spaces between vehicles and thus the road spaces can be exploited more fully and efficiently when the proportion of motorcycles increases. However, overcrowded and congested lanes could impede their filtering behaviour. To investigate the effects of the proportion of motorcycles on their PCUs, this variable was manipulated at five levels, 0%, 25%, 50%, 75% and 100%.

4. Advanced stop line: The installation of a motorcycle reservoir behind the stop line is an important factor affecting the number of motorcycles able to make a swift start at the beginning of a green period. Hence, the PCU equivalents were estimated both with and without the layout of an advanced stop line at the beginning of green periods. The length of this motorcycle reservoir was set to be 5 m.

The resulting estimated motorcycle PCU values were analysed using different combinations of these factors at different levels for each traffic environment. There is no difference between having and not having an advanced stop line in a flow made up entirely (100%) of motorcycles and the saturation flow rate is then not affected by an advanced stop line. Hence, this and other redundant conditions were omitted. A total of 168 treatments were analysed in this study, as shown in Table 2.

Table 2 Variables considered in the analysis

| Traffic environment | Lane width (m) | Number of lanes | Proportion of motorcycle (%) | Advanced stop line | Number of treatments |
|---|---|---|---|---|---|
| Beginning of green | 2.0, 2.5, 3.0 and 3.5 | 1, 2 and 3 | 0%, 25%, 50%, 75% and 100% | Yes | 60 |
| | | | 0%, 25%, 50% and 75% | No | 48 |
| Saturation flow | 2.0, 2.5, 3.0 and 3.5 | 1, 2 and 3 | 0%, 25%, 50%, 75% and 100% | No | 60 |

## THE PCUS OF MOTORCYCLES

The PCUs of motorcycles are estimated by using the data generated from the simulator. The estimation results are shown in Figure 3, Appendix A and Appendix B. The effects of the lane width, the proportion of motorcycles, the number of lanes, the installation of an advanced stop line and the traffic speed are analysed.

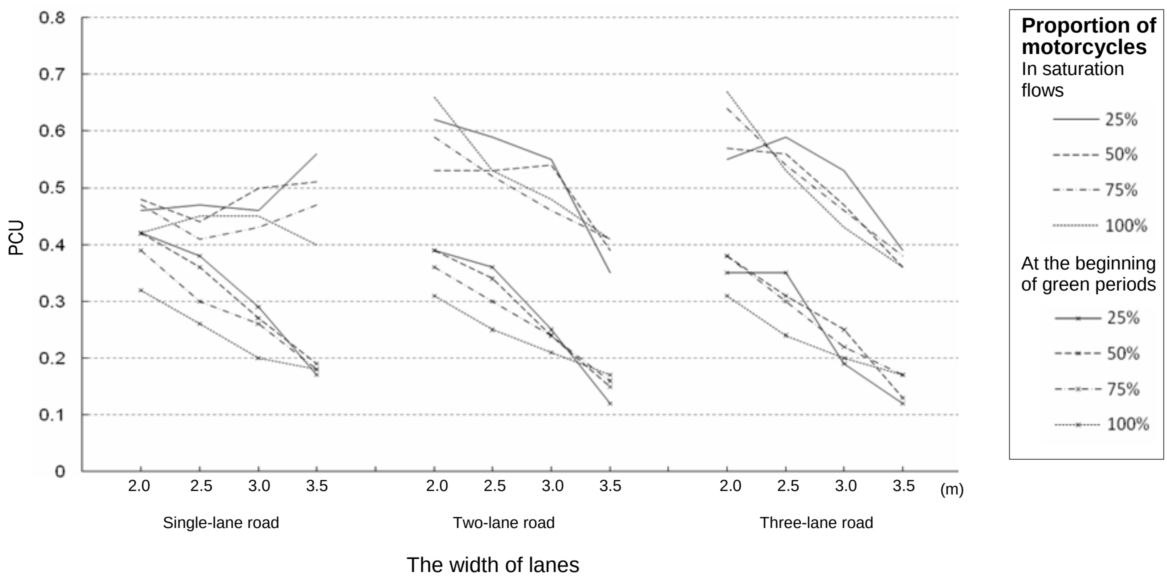


Figure 3 The PCUs of motorcycles

## PCUs of motorcycles at the beginning of a green period

At the beginning of a green period, vehicles at the head of a queue have the freedom to choose their speeds and accelerations. When this area can be used more efficiently, the capacity of this intersection can be higher.

### *The effects of lane widths*

The results show that motorcycles have lower PCUs when moving along roads with wider lanes. A wide lane facilitates filtering behaviour and thus increases the number of motorcycles at the front of a queue. Figure 3 illustrates this trend and this is confirmed by the Wilcoxon signed rank test (see Appendix D) as well as the ex-post regression analysis presented later in the section. Generally, when motorcycles have a greater opportunity to filter through the queue, e.g. the width of the lanes is at the level of 3.5 m, the motorcycle PCU values can be as low as around 0.15 at the beginning of a green period.

### *The effects of the number of lanes*

Regarding to the effects of the lane numbers on PCUs, the bivariate analysis between the PCU and the number of lanes indicates the correlation between these two variables is not significant (Pearson's r=-0.154, n=48, p=0.296). However, without assuming that the samples are distributed normally, the Wilcoxon signed rank test indicates that motorcycles have lower PCUs in a road with more lanes (see

Appendix C). The reasons could be: (1) motorcycles in a multi-lane road have more freedom to choose their paths and have better chances to filtering through a queue; (2) in this experimental environment, the gap between two passenger cars is larger than that between the kerb and a passenger car. The latter factor might be more critical as the Wilcoxon signed rank test result shows that the PCU difference between the three-lane and the two-lane roads is smaller than that between the two-lane and the single-lane roads. These results are consistent with the observation of Robertson (2002a) who found that less filtering behaviour was observed between the kerb and the inner lane vehicle tracks than between lanes. However, this should depend on the traffic environment. When motorcycles are moving in a single lane link with a wide hard shoulder, they could perhaps filter through congestion by using the shoulder. Based on these analyses, the effects of the number of lanes on PCU values cannot be confirmed yet. Further studies are needed to understand this issue, and the interactions between these variations and under different regulatory regimes.

### *The effects of vehicle composition*

The Wilcoxon signed rank test does not support the assumption that motorcycles have lower PCUs when their proportion is higher. In some scenarios, motorcycles' low PCUs are observed despite low motorcycle proportions in the traffic flow. For example, a motorcycle staying in the space between two passenger cars at the head of a queue would have a PCU equivalent as low as 0. This means that the lateral positioning of motorcycles at the head of a queue plays an important role, and greater detail in modelling and observation data would be valuable, and possibly include bicycle traffic as these interactions are of regulatory as well as capacity interest. The flow with large lane width and a low motorcycle proportion in the traffic flow also causes low PCU values. Consequently, the proportion of motorcycles in the traffic flow does not show a strong relationship with the measured PCU values.

### *The effects of the advanced stop lines*

While examining the benefits of installing an advanced stop line, it is found that an advanced stop line cannot increase the capacity of an intersection unless motorcycles can make good use of the area. Figure 4 shows the differences of PCUs after the installation of an advanced stop line, where a negative value means the introduction of an advanced stop line will reduce the PCU values further. The results show that motorcycle PCUs decrease only when the motorcycle reservoir can be used efficiently, i.e. when the traffic has a high proportion of motorcycles or the road is in wide lanes or the advanced stoplines are extended across the full set of lanes. Based on these analyses, a designated lead-in motorcycle lane to help motorcycles gain access to the motorcycle reservoir is necessary to secure the available increase in road capacity.

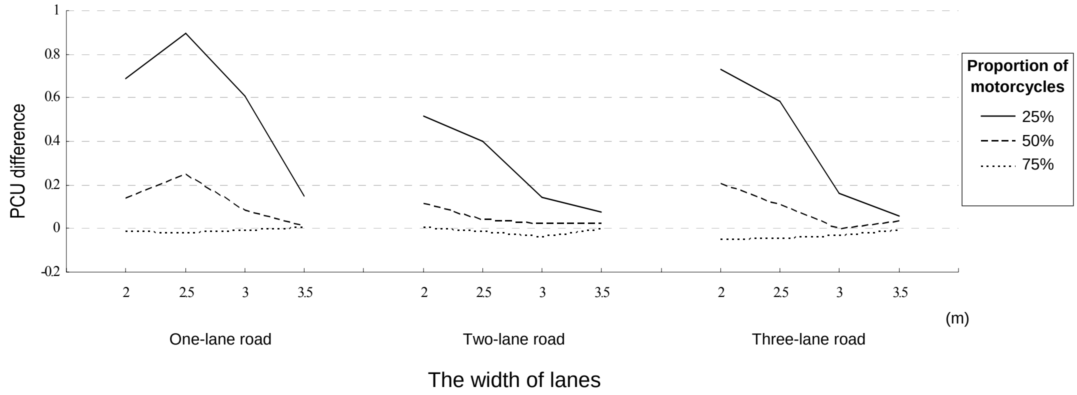


Figure 4 The PCU differences after the installation of an advanced stop line

## PCUs of motorcycles in a saturation flow

The saturation flow rate is an important parameter in capacity analysis. The central plateau region in a flow rate against time diagram (see Figure 1) is used to estimate the PCUs. In saturation flow, the filtering or overtaking behaviour of motorcycles is not obvious. The main behaviour pattern affecting the PCUs of motorcycles is to move alongside another vehicle in the same lane.

### *The effects of the variables*

The simulation results indicate that both the proportion of motorcycles and the number of lanes do not have a significant impact on the values estimated for motorcycle PCUs (see Figure 3 and Appendix D). The crowded road space in a saturation flow makes the overtaking or filtering behaviour of motorcycles difficult and changing the proportion of motorcycles or the number of lanes does not make a difference. In this traffic environment, the only variable which can affect the PCU values of motorcycles is the width of lanes, under the condition of multiple lanes. Wider lanes in a multiple-lane road do facilitate a motorcycle to move alongside another vehicle in the same lane, or pass it while it is stationary, and thus lower the value of the motorcycle PCU equivalent.

It is found that the PCUs in multi-lane roads with narrow lane widths are higher than those in single-lane roads. This can be linked to the loose lane discipline of motorcycles. In saturation flow, the filtering or overtaking behaviour of motorcycles is not obvious. When a motorcycle is moving between two lanes without overtaking, it could cause disturbances to the successive passenger cars in both lanes, i.e. a motorcycle could occupy two lanes simultaneously, particularly when the lane widths are small. Any disturbances caused by the presence of motorcycles both between and within lanes are finally encapsulated in a higher PCU value for motorcycles.

## Modelling the PCU values of motorcycles – an ex-post analysis

An ex-post analysis of the simulation results is performed by fitting a multiple linear regression model which describes the relationship between the PCU values and the relevant traffic conditions. First, the bivariate relationships between the PCU values and the independent variables are examined. It is found that there is a linear relationship between PCU values and the lane widths in multiple-lane saturation flows and at the beginning of green periods (Pearson's r=-0.773, n=32, p<0.0005 and Pearson's r=-0.914, n=48, p<0.0005 respectively). Such linear relationships can also be observed in Figure 3. The proposed model is:

$$pcu_{saturation,width} = a_0 + a_1 \times saturation + a_2 \times width \quad (2)$$

where

- *saturation* : dummy variable. *saturation* =1 when in a multiple-lane saturation flow and *saturation* =0 when at the beginning of green periods.
- *width* : the width of lanes.
- $a_0$, $a_1$ and $a_2$ : coefficients.

The outputs of this linear regression analysis are shown in Table 3. The r-square value of this regression is 0.937, indicating that this model fits the data well. The coefficients indicate that the PCU values of motorcycles at the beginning of green periods are on average 0.237 lower than those in multiple-lane saturation flows, and the PCU values are reduced by 0.143 with every 1.0 m increase in the lane width. All the coefficients are significantly different from 0 (t test, p< 0.0005).

Table 3 The suggested PCUs for motorcycles in a saturation flow

| | Estimate | Std. Error | T | Sig. |
|---|---|---|---|---|
| $R^2$ | 0.937 | - | - | - |
| $a_0$ | 0.661 | 0.021 | 31.190 | 0.000 |
| $a_1$ | 0.237 | 0.009 | 27.878 | 0.000 |
| $a_2$ | -0.143 | 0.007 | -19.139 | 0.000 |

The regression lines and the scatter plot of the samples are plotted in Figure 5, which illustrates the scattered pattern of the residuals is constant across cases. The residuals are examined and found distributing normally (Kolmogorov-Smirnov test for normality, n=80, Sig. value=0.200).

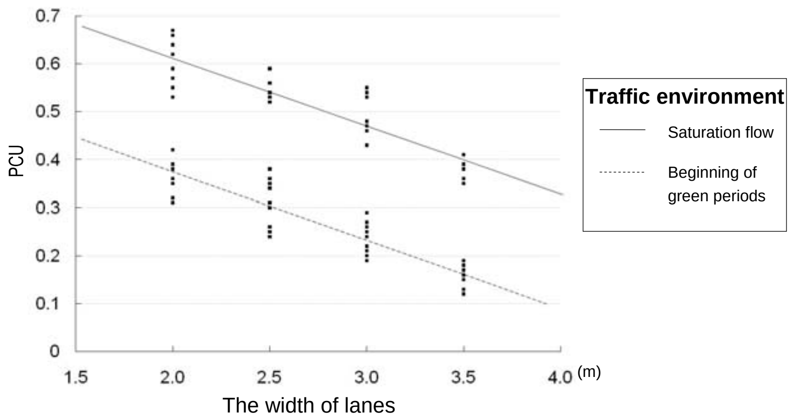


Figure 5 The scattered plot of the samples and the regression lines of the model

In single lane saturation flow, the PCU of motorcycles is estimated to be 0.46: the mean of the PCU values in this category. Otherwise, the PCU is linear related to the width of the lanes. It can be described by the following regression model. Table 4 shows the values in different conditions.

$$pcu_{saturation,width} = 0.661 + 0.237 \times saturation - 0.143 \times width, \qquad 2.0 \le width \le 3.5. \tag{3}$$

Table 4 Suggested PCUs for motorcycles

| Lane width | Beginning of green periods | Saturation flow | |
|---|---|---|---|
| | | Single lane | Multiple lane |
| **0.20** | 0.38 | 0.46 | 0.61 |
| **0.25** | 0.30 | 0.46 | 0.54 |
| **0.30** | 0.23 | 0.46 | 0.47 |
| **0.35** | 0.16 | 0.46 | 0.40 |

# CONCLUSION AND FUTURE WORK

The PCUs of motorcycles are measured under two traffic environments: at the beginning of a green period and in a saturation flow, by using an agent-based traffic simulation system. The influences of four variables: the advanced stop line, the number of lanes, the width of lanes and the proportion of motorcycles are analysed.

The results show that motorcycles have various PCUs depending on the traffic environment in which they are measured and applied. At the beginning of green periods, the key factor affecting the PCUs is the number of motorcycles able to filter to the head of the queue. It is found that there is a significant linear relationship between PCU values and lane widths. However, the proportion of motorcycles in the traffic flow is found to have no significant affect on the PCU values. Further studies are needed to confirm influences of the number of lanes.

In saturation flow, the key factor affecting motorcycles PCU values is the capability of motorcycles to move alongside another vehicle in the same lane, moving or stationary. On a multiple-lane road, the effects of the lane width are significant whereas these effects are not significant on a single-lane road. In addition, the proportion of motorcycles and the number of lanes had no significant impact on the PCU values found.

Based on the simulation results, an ex-post analysis was done using multi-linear regression. This model indicates that the PCU values of motorcycles at the beginning of green periods are on average 0.237 lower than those in multiple-lane saturation flows. In addition, the PCU values decreased by 0.143 with every 1.0 m increase in the lane width. The PCU values that could be used for capacity analysis of different traffic conditions are suggested using this model.

The present paper is concerned with the conditions of the beginning of green periods and saturation flow, in zones where there are no related turning movements. However, at intersections motorcycles show a further range of behaviours that differ from passenger cars. Thus, the application to complex and simple turning movements in multiple-lane movements remains to be explored. In addition, this approach can be a possible prototype for estimating the PCUs of the family of single-track two-wheelers as this family have some similar behaviour patterns. For example, estimating the PCUs for bicycles would be a good topic for the following work as the need is just as urgent, and mixes of powered and unpowered two wheeled vehicles is a live issue in designated lane access and use.

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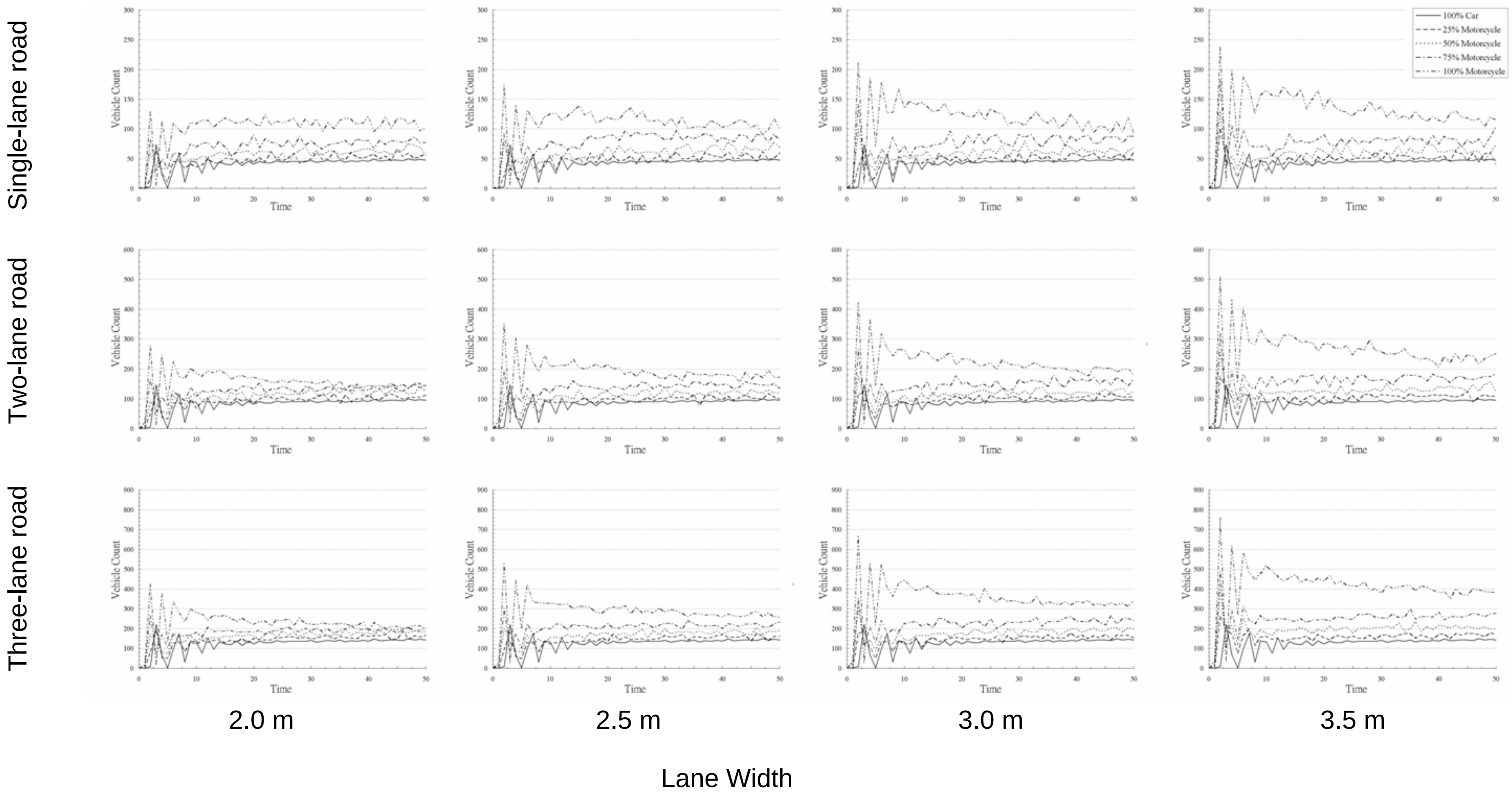
# APPENDIX A THE PCUS OF MOTORCYCLES IN ALL SCENARIOS

| | | Proportion of motorcycles | Single-lane road | | | | Two-lane road | | | | Three-lane road | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 2.0m | 2.5m | 3.0m | 3.5m | 2.0m | 2.5m | 3.0m | 3.5m | 2.0m | 2.5m | 3.0m | 3.5m |
| **Beginning of green** | without an advanced stop line | 25% | 0.42 | 0.38 | 0.29 | 0.17 | 0.39 | 0.36 | 0.25 | 0.12 | 0.35 | 0.35 | 0.19 | 0.12 |
| | | 50% | 0.42 | 0.36 | 0.27 | 0.19 | 0.39 | 0.34 | 0.24 | 0.15 | 0.38 | 0.31 | 0.25 | 0.13 |
| | | 75% | 0.39 | 0.30 | 0.26 | 0.18 | 0.36 | 0.30 | 0.24 | 0.16 | 0.38 | 0.30 | 0.22 | 0.17 |
| | with an advanced stop line | 25% | 1.11 | 1.28 | 0.90 | 0.31 | 0.90 | 0.76 | 0.39 | 0.19 | 1.08 | 0.93 | 0.35 | 0.18 |
| | | 50% | 0.56 | 0.61 | 0.35 | 0.20 | 0.50 | 0.38 | 0.26 | 0.17 | 0.58 | 0.41 | 0.25 | 0.16 |
| | | 75% | 0.37 | 0.28 | 0.25 | 0.18 | 0.37 | 0.29 | 0.20 | 0.16 | 0.33 | 0.26 | 0.19 | 0.16 |
| | | 100% | 0.32 | 0.26 | 0.20 | 0.18 | 0.31 | 0.25 | 0.21 | 0.17 | 0.31 | 0.24 | 0.20 | 0.17 |
| **Saturation flow** | | 25% | 0.46 | 0.47 | 0.46 | 0.56 | 0.62 | 0.59 | 0.55 | 0.35 | 0.55 | 0.59 | 0.53 | 0.39 |
| | | 50% | 0.48 | 0.44 | 0.50 | 0.51 | 0.53 | 0.53 | 0.54 | 0.39 | 0.57 | 0.56 | 0.47 | 0.36 |
| | | 75% | 0.47 | 0.41 | 0.43 | 0.47 | 0.59 | 0.52 | 0.46 | 0.41 | 0.64 | 0.54 | 0.46 | 0.38 |
| | | 100% | 0.42 | 0.45 | 0.45 | 0.40 | 0.66 | 0.53 | 0.48 | 0.41 | 0.67 | 0.53 | 0.43 | 0.36 |

# APPENDIX B VEHICLE COUNTS AT GREEN PERIODS FROM THE SIMULATION RESULTS



# APPENDIX C WILCOXON SIGNED RANK TEST RESULTS

Table C-1 Wilcoxon signed rank test for the PCUs at the beginning of a green period

| | Tested hypothesis | z-value | p-value (two-tailed) | Comment |
|---|---|---|---|---|
| **Difference between lane width** | $PCU_{2.0m}=PCU_{2.5m}$ | -3.059 | 0.002 | Significantly different |
| | $PCU_{2.5m}=PCU_{3.0m}$ | -3.059 | 0.002 | Significantly different |
| | $PCU_{3.0m}=PCU_{3.5m}$ | -3.059 | 0.002 | Significantly different |
| **Difference between motorcycle proportion** | $PCU_{25\%mc}=PCU_{50\%mc}$ | -0.392 | 0.695 | Not significantly different |
| | $PCU_{50\%mc}=PCU_{75\%mc}$ | -1.726 | 0.084 | Not significantly different |
| | $PCU_{25\%mc}=PCU_{75\%mc}$ | -0.863 | 0.388 | Not significantly different |
| | $PCU_{75\%mc}=PCU_{100\%mc}$ | -2.589 | 0.010 | Significantly different |
| **Difference between number of lanes** | $PCU_{1\text{-}lane}=PCU_{2\text{-}lane}$ | -3.361 | 0.001 | Significantly different |
| | $PCU_{2\text{-}lane}=PCU_{3\text{-}lane}$ | -2.069 | 0.039 | Significantly different |

Table C-2 Wilcoxon signed rank test for the PCUs in saturation flow

| | | Tested hypothesis | z-value | p-value (two-tailed) | Comment |
|---|---|---|---|---|---|
| **Difference between lane width** | Single-lane road | $PCU_{2.0m}=PCU_{2.5m}$ | -0.730 | 0.465 | Not significantly different |
| | | $PCU_{2.0m}=PCU_{3.0m}$ | -0.365 | 0.715 | Not significantly different |
| | | $PCU_{2.0m}=PCU_{3.5m}$ | -1.095 | 0.273 | Not significantly different |
| | | $PCU_{2.5m}=PCU_{3.0m}$ | -1.095 | 0.273 | Not significantly different |
| | | $PCU_{2.5m}=PCU_{3.5m}$ | -1.461 | 0.144 | Not significantly different |
| | | $PCU_{3.0m}=PCU_{3.5m}$ | -0.730 | 0.465 | Not significantly different |
| | Multi-lane road | $PCU_{2.0m}=PCU_{2.5m}$ | -1.820 | 0.069 | Not significantly different |
| | | $PCU_{2.0m}=PCU_{3.0m}$ | -2.380 | 0.017 | Significantly different |
| | | $PCU_{2.0m}=PCU_{3.5m}$ | -2.521 | 0.012 | Significantly different |
| | | $PCU_{2.5m}=PCU_{3.0m}$ | -2.380 | 0.017 | Significantly different |
| | | $PCU_{2.5m}=PCU_{3.5m}$ | -2.521 | 0.012 | Significantly different |
| | | $PCU_{3.0m}=PCU_{3.5m}$ | -2.521 | 0.012 | Significantly different |
| **Difference between motorcycle proportion** | | $PCU_{25\%mc}=PCU_{50\%mc}$ | -1.490 | 0.136 | Not significantly different |
| | | $PCU_{25\%mc}=PCU_{75\%mc}$ | -1.647 | 0.099 | Not significantly different |
| | | $PCU_{25\%mc}=PCU_{100\%mc}$ | -1.334 | 0.182 | Not significantly different |
| | | $PCU_{50\%mc}=PCU_{75\%mc}$ | -0.863 | 0.388 | Not significantly different |
| | | $PCU_{50\%mc}=PCU_{100\%mc}$ | -0.706 | 0.480 | Not significantly different |
| | | $PCU_{75\%mc}=PCU_{100\%mc}$ | -0.356 | 0.722 | Not significantly different |
| **Difference between number of lanes** | | $PCU_{1\text{-}lane}=PCU_{2\text{-}lane}$ | -1.810 | 0.070 | Not significantly different |
| | | $PCU_{1\text{-}lane}=PCU_{3\text{-}lane}$ | -1.241 | 0.215 | Not significantly different |
| | | $PCU_{2\text{-}lane}=PCU_{3\text{-}lane}$ | -0.827 | 0.408 | Not significantly different |