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Research Article

Development of On-Road Exhaust Emission and Fuel Consumption Models for Motorcycles and Application through Traffic Microsimulation

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This study developed on-road exhaust emission and fuel consumption models for application in traffic microsimulations to estimate motorcycle emissions and fuel consumption in an Asian developing city. The motorcycle onboard measurement system was developed to instantaneously measure and continuously record on-road driving data, including the speed-time profile, exhaust emissions, and fuel consumption per second. The test motorcycle was driven on roads around Khon Kaen City, Thailand, to collect on-road driving data during the morning peak hours for a total of 112 hours. The collected on-road driving data were applied to develop on-road exhaust emission and fuel consumption models using regression analysis. The models were developed with high correlations among the amount of exhaust emissions and fuel consumption and the instantaneous speed and acceleration rate. The developed models were applied with a traffic microsimulation to evaluate the exclusive zone for motorcycles stopping at a signalized intersection. The evaluation results reveal that it could improve the level of intersection service by decreasing travel times, delays, and queue lengths at intersections, as well as by reducing the fuel consumption and emissions of vehicles travelling through intersections compared with these values under the existing conditions.

1. Introduction

Recently, the number of registered motorcycles in Asian developing countries has increased rapidly. In Thailand, the number of registered motorcycles increased to 20 million vehicles, representing 56% of all vehicles [1]. In Hanoi, Vietnam, motorcycles have the largest share, accounting for more than 90% of the road transport fleet [2]. This high demand has increased fuel consumption and is a direct cause of a large amount of air pollution emissions. Sahu et al. [3] estimated that motorcycles emitted approximately 37% of the total emissions from carbon monoxide (CO) in on-road transport in India. Fukuda et al. [4] found that motorcycles consumed about 30% of fuel consumed by passenger cars and emitted about 27% of carbon dioxide (CO_2) emitted by passenger cars in Khon Kaen City, Thailand. The Asian Development Bank, ADB [5], stated that the MC fleet contributed approximately 54% of CO and hydrocarbon (HC) pollution at a Hanoi roadside during morning rush hours. Wang et al. [6] estimated that motorcycles emitted approximately 45.0% of the Volatile Organic Compounds (VOC) and approximately 36.3% of the Particulate Matter (PM) of the total emissions from vehicles in Shanghai, China. Thus, fuel consumption and emissions from motorcycles in developing Asian cities are problems that require immediate action.

To reduce fuel consumption and emissions from the transport sector, the World Conference on Transport Research Society (WCTRS) [7] proposed the CUTE matrix, introducing three strategies: AVOID, SHIFT, and IMPROVE. In motorcycle-dominated countries, researchers have proposed measures according to this matrix, including SHIFT (e.g., shift to public transport [8]) and IMPROVE (e.g., improve motorcycle conformance to the EURO3 standard [9], as well as changing motorcycles to electric motorcycles [10]). To evaluate the proposed measures, the models and factors regarding transportation, fuel consumption, and emissions, particularly for motorcycles, are important. At the macro level, the demand forecasting models require fuel consumption and emission factors as the model input. Previous studies, for example, those of Kumar et al. [11] and Zamboni et al. [12], developed emission and fuel consumption factors for motorcycles to serve this purpose. At the micro level, driving parameters, driving behavior models, and emission and fuel consumption models are required to simulate the traffic in a specific area. From a literature review, many researchers explored driving parameters and developed driving behavior models for motorcycles that were necessary for traffic microsimulation (see Powell [13], Minh et al. [14–16], Cho and Wu [17], and Satiennam et al. [18]). The emission and fuel consumption model, however, was developed for various types of vehicles, including passenger cars, vans, trucks, and buses (see Yu [19], Ahn et al. [20], Rakha et al. [21], Wang et al. [22], Kamarianakis et al. [23], and Rakha et al. [24]); this model was not available for motorcycles. These important models present the instantaneous amount of emissions and fuel consumption corresponding to characteristics of the speed profile, for example, instantaneous speed (km/hr)/acceleration (m/s^2) of the vehicle. The lack of emission and fuel consumption models for motorcycles limits the evaluation capability of the proposed measures to reduce fuel consumption and emissions from the transport sector in motorcycle-dominated cities. The onboard measurement is another interesting approach that can collect driving pattern, fuel consumption, and emissions under real-world traffic and load conditions rather than simulating loads in laboratory. The recent study by Seedam et al. [25] developed the onboard measurement to collect on-road driving parameters of motorcycle driving on a congested signalized urban corridor. It found that proportion of idle time significantly influenced fuel consumption and emissions; nevertheless aggressive driving behavior, hard acceleration, and deceleration did not have the same kind of influence. Many measures were recommended to reduce the stop and delay of motorcycle at signalized intersections and their evaluation is necessary.

Therefore, the objectives of this study were to develop an on-road exhaust emission and fuel consumption model for motorcycles and to present the application of the developed models for evaluating the traffic management strategy for motorcycles through traffic microsimulation. In this paper, the next section describes the research methodology. Section 3 presents the results and discussion. Section 4 presents the conclusions and recommendations.

2. Research Methodology

This section explains the research methodology procedure as displayed in Figure 1. The research methodology is classified into two main sections. In the model development section, there are three steps: the development of an onboard motorcycle measurement system, on-road driving data collection, and the development of on-road exhaust emission and fuel consumption models. In the model application section, there are three steps: a survey of road geometry and traffic data, the development of a traffic microsimulation model, and the evaluation of the traffic management strategy for motorcycles. Each approach in the model development and application section will be described in the following subsections.

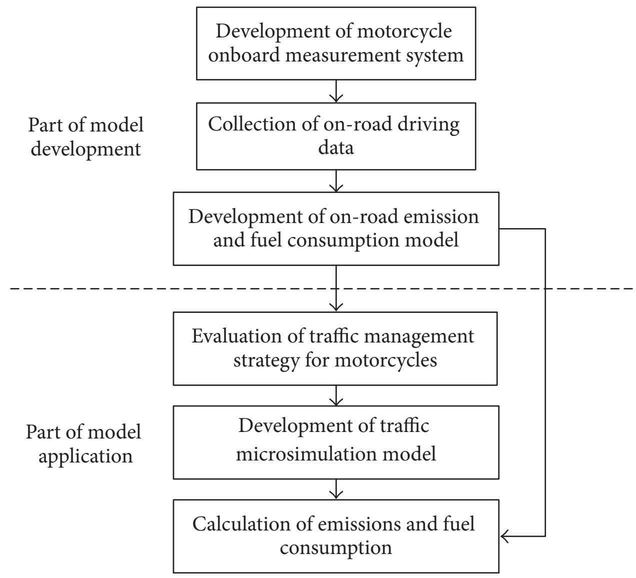

Figure 1: Research procedure.

2.1. Onboard Measurement System Development. This study developed an onboard measurement system based on previous researches [25, 28, 29] to instantaneously measure and continuously record the speed-time profile, fuel consumption, and exhaust emissions of motorcycles when driving on a road network. The developed system consists of several measurement units, including the GPS sensor, the rear wheel speed sensor, the mobile exhaust gas analyzer, and the fuel consumption sensor. The selected motorcycle was a 4-stroke 113 CC motorcycle, a small-sized motorcycle that is normally used in developing Asian cities. The installed measurement units are positioned on the test motorcycle as displayed in Figure 2.

As shown in Figure 2, the GPS sensor was used to identify the location of the motorcycle as it is driven. The rear wheel speed sensor was designed to measure the motorcycle speed. The magnetic sensor was installed on the rear wheel to detect the wheel rotation every second. While the wheel is rotating, the magnetic poles produce pulses. The pulse is converted to a voltage signal using a voltage converter circuit. Finally, the microcontroller converts this voltage signal to speed-time data. A mobile exhaust gas analyzer, namely, the INFRALYT SMART, was installed on the rear of the motorcycle to measure the amount of emissions, including CO, CO_2, HC, and nitrogen oxides (NOx). The analyzer was calibrated by the manufacturer with an error of less than 1% (its accuracy according to OIML Class 0, [30]). The fuel consumption sensor and the electric flow meter, namely, the SENSIRION (model SLQ-HC60), were installed to measure the amount of fuel consumption at the fuel tube connecting the fuel tank to the carburetor. This model could sensitively measure

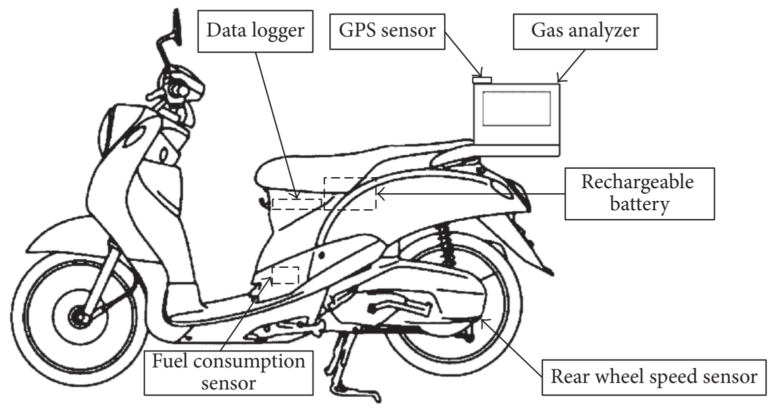

FIGURE 2: Components of the developed onboard measurement system.

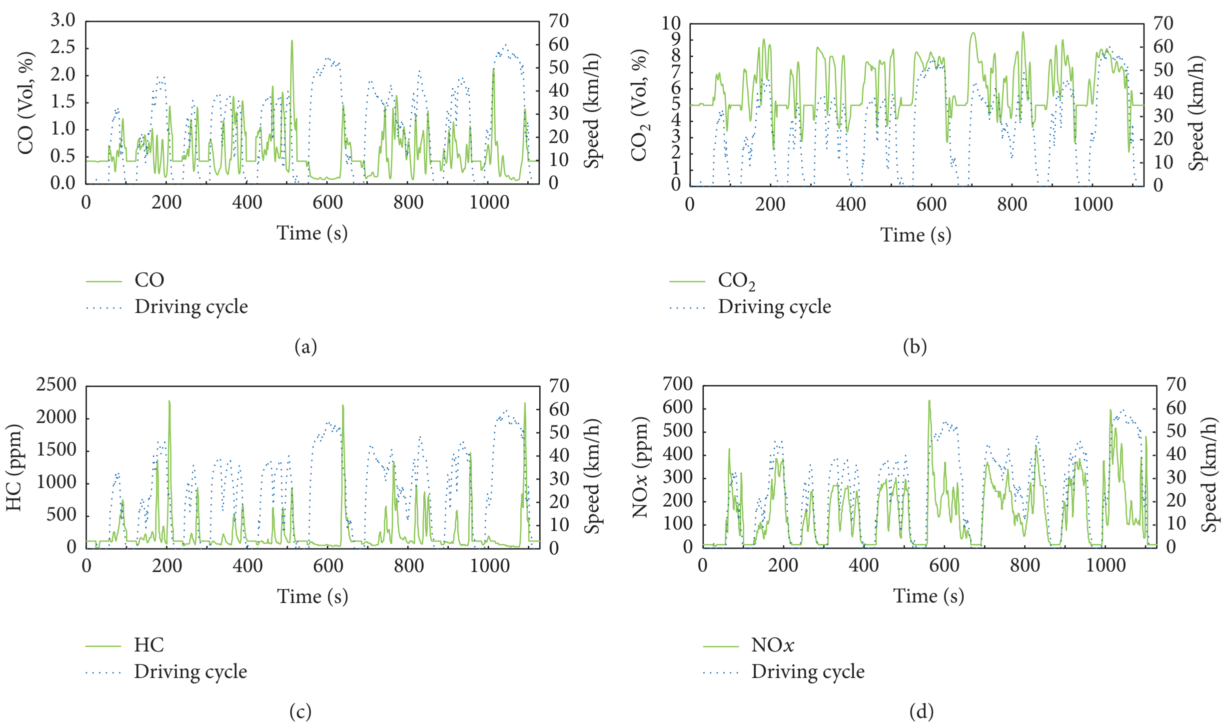

FIGURE 3: Motorcycle speed-time profile with exhaust emissions.

the lowest flow with high accuracy and a fast response time. Data from the previously mentioned measurement units were processed and recorded in the data logger. The processor processes and records data into memory storage every second. In addition, a rechargeable battery is used to supply electric power to the data logger.

To check the relationship between the motorcycle speed and the measured exhaust emissions, the test motorcycle was driven on roads to measure its speed-time data and the corresponding exhaust emissions. The driving cycle, a statistical summary of collected speed-time data, was plotted comparatively with the exhaust emissions as shown in Figure 3. As expected, while the speed increased with constant acceleration, the amount of emitted CO_2 increased, as shown in Figure 3(b). This result is because the engine was combusting more gasoline and air, hence producing more CO_2. Once the speed increased with increasing acceleration, the amount of emitted CO and NOx increased, as shown in Figures 3(a) and 3(d), respectively. This finding exists because increasing acceleration caused imperfect combustion, which emits more CO and NOx. While the speed decelerated, the amount of emitted HC increased, as shown in Figure 3(c), because deceleration reduces engine combustion; the remaining combusted gasoline and air, therefore, increased. These results imply that the developed system could reasonably measure and record the on-road driving data from the test motorcycle.

2.2. On-Road Driving Data Collection. This study selected Khon Kaen City as a study area because this city is one of

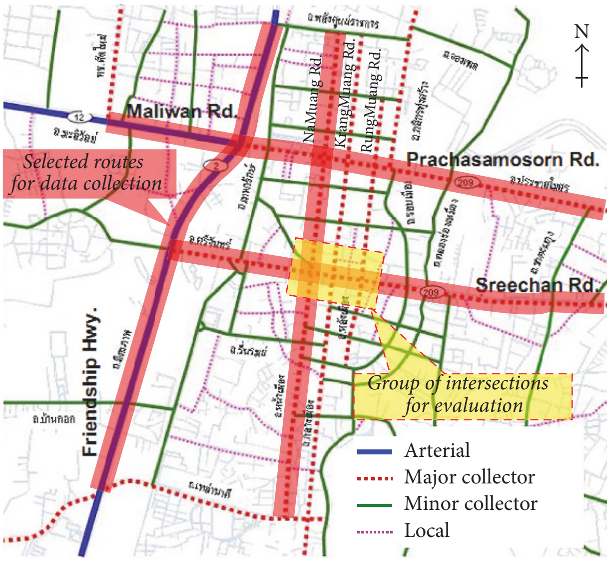

Figure 4: Selected routes for data collection and a group of intersections for evaluation.

the Asian developing cities having a large number of motorcycles, 30% of the mode share [31], and currently encounters congested traffic conditions. Khon Kaen Province is located in the Northeast of Thailand. Khon Kaen City covers an area of 228 km^2. Recently, it was determined that the city's population is approximately 250,000. The test motorcycle, with an installed onboard measurement system, was driven randomly on selected routes in Khon Kaen City, as shown in Figure 4. Data collections were conducted during the weekday's morning peak hours between 7:00 and 9:00 a.m. for 112 hours.

2.3. On-Road Exhaust Emission and Fuel Consumption Model Development. The speed-time data, on-road exhaust emissions, and fuel consumption collected every second were applied to develop the on-road exhaust emission and fuel consumption models, using the regression analysis technique. This study reviewed many previous studies to determine the mathematical format that would provide the best fit with the collected data. A few studies, for example, Kamarianakis et al. [23], applied a linear form, but many studies, including Penic and Upchurch [32], Yu [19], Ahn et al. [20], Rakha et al. [21], and Wang et al. [22], applied a nonlinear form to develop the emission and fuel consumption models. Therefore, the various mathematical forms according to previous studies were tested in regression analysis to determine the most appropriate model. The mathematical forms, for example, the linear form, the exponential form, and the third-order polynomial form, with the independent variables, for example, the instant speed and the instant acceleration, were tested. The regression model was developed at the 95% confidence level. For the development of emission models for other vehicle types, the study applied the emission data measured in the Automotive Emissions Laboratory of the Pollutant Control Department [33] to develop emission models according to fuel type, including gasoline and diesel. The emission data were further applied to calculate the fuel consumption for developing the fuel consumption models.

2.4. Evaluation of a Traffic Management Strategy for Motorcycles. This section presents the application of the developed models in evaluating a traffic management strategy for motorcycles through traffic microsimulation. This study selected the exclusive zone for motorcycle stopping at a signalized intersection as a strategy to improve traffic conditions because it has never been evaluated in terms of reducing fuel consumption and emissions. This exclusive zone is an area for motorcycles located between the stop line of a signalized intersection and a stop line for other vehicles, as displayed in Figure 5. The area occupied the entire lane width, and its length was normally equal to the length of a motorcycle (2 meters) or longer, depending on the number of motorcycles. The logic behind this implementation is that the motorcyclist usually dominates the larger vehicle queue because of its smaller size and stops in front of the queue for advance starting at the signalized intersection. However, the larger vehicle occasionally stops close to the stop line; therefore, no area is available for motorcycles. This strategy has been implemented in several Asian countries that have a high mode share of small-sized motorcycles, such as Taiwan and Thailand.

This study planned to implement the exclusive zone for motorcycle stopping at a group of three signalized intersections located along Sreechan road, as displayed in Figure 4. This road is a 2-lane undivided road with a roadside parking lane. This road section is a main urban arterial road of Khon Kaen City, with a high number of travelling motorcycles. The conditions after implementation of the exclusive zone for motorcycles were compared with the existing conditions. The traffic microsimulation model was applied to simulate the before and after traffic conditions. The traffic measures of effectiveness (MOEs), emissions, and fuel consumption were considered as evaluation criteria. The traffic MOEs consist of the average travel time, average delay, and average queue length of motorcycles, other vehicles, and the total system. The emissions (CO_2, CO, HC, and NOx) and fuel consumption of motorcycles, other vehicles, and the total system were also evaluated.

2.5. Development of Traffic Microsimulation Model. To simulate the motorcycle mix in traffic, traffic simulation software that enables a simulation of the behavior of individual vehicles was required. This study selected the VISSIM software because of its ability to model the exclusive zone for motorcycle stopping at a signalized intersection. The traffic flow model in VISSIM has a psychophysical car following model for longitudinal vehicle movement and a rule-based algorithm for lateral movements. The approach and parameters of this model are based on the research of Wiedemann in 1974 and 1999 [34]. Moreover, VISSIM can measure the speed-time profile of individual vehicles, while they travel past signalized intersections; this was necessary information as input data for emissions and fuel consumption models. The study modeled the lateral behavior of the motorcycles when the motorcycles overtake other slower or stopping vehicles

Figure 5: Example of the exclusive zone for motorcycle stopping at a signalized intersection in Thailand.

Table 1: Approaching, turning, and crossing speeds at intersections by vehicle type.

Average desired speed (km/h)	Motorcycle (MC)	Passenger car (PC)	Pick-up truck/van (LT)	6-Wheel truck/bus (HT)
Approaching	44.54	44.36	42.49	41.54
Crossing	28.07	26.38	25.16	23.37
Right turning	23.65	19.84	18.90	18.17
Left turning	16.99	13.74	13.63	11.53

for the signal waiting time in the exclusive zone by setting the parameters for lateral driving behavior. The motorcycle could overtake either on the left or on the right of other vehicles in the same lane with a minimum lateral distance according to the surveyed real-world behavior. Additionally, the exclusive zone for motorcycles was created by setting two stop lines, one for the motorcycles located close to the intersection and another one for other vehicles located next to the exclusive zone.

The road geometry and traffic data were collected for the development of a traffic simulation model. The four vehicle types considered in this study were motorcycles (MC), passenger cars (PC), pickup trucks and vans (LT), and trucks and buses (HT). The turning count data by vehicle type was collected during morning peak hours (7:30–8:30 a.m.) for development of OD matrices. These OD matrices were input into VISSIM through the function of turning movements by vehicle type. The approaching, turning, and crossing speeds at intersections by vehicle type were surveyed using the spot speed method. The surveyed results, presented in Table 1, were applied to develop the desired speed distribution by vehicle type in VISSIM.

The study followed the guidelines proposed by FHWA [35] for application in the traffic microsimulation software. Before application of the traffic microsimulation model, it was necessary to calibrate the developed traffic microsimulation to be as close to the real-world traffic conditions as possible by adjusting the driving behavior parameters [36]. In the calibration process, this study simulated the OD matrix on the developed network. The criteria for traffic measures resulting from the simulation, including traffic flow and the maximum queue length, were compared with the field. The differences and GEH statistics were compared with acceptance targets proposed by the Wisconsin Department of Transport [26] and Ahmed [27]. The driving behavior parameters were adjusted until the criteria for traffic measures passed the acceptance targets.

2.6. Calculation of Emissions and Fuel Consumption. The results from the traffic microsimulation model, including the instantaneous velocity and acceleration of each individual vehicle, were applied with the developed emissions and fuel consumption models to calculate the emissions and fuel consumption. For each vehicle, its total emissions and fuel consumption were calculated from a summary of instantaneous values at each second. Finally, the total emission and fuel consumption of all vehicles were calculated using the following equations:

$$\text{total emission} = \sum_{k}^{4}\sum_{j}^{m}\sum_{i}^{n}\text{instant emission of a vehicle}, \quad (1)$$

$$\text{total fuel consumption} = \sum_{k}^{4}\sum_{j}^{m}\sum_{i}^{n}\text{instant fuel consumption of a vehicle}, \quad (2)$$

where $i = 1, 2, 3, \ldots, n$ (number of time steps in second), $j = 1, 2, 3, \ldots, m$ (number of vehicles), $k = 1$, motorcycle, 2, passenger car, 3, pickup truck and van, and, 4, truck and bus.

3. Results and Discussion

This section presents the results of the development of the traffic microsimulation model and the development of on-road exhaust emissions and fuel consumption models, as well as the evaluation of exclusive zones for motorcycle stopping at signalized intersections.

3.1. Results of the Model Calibration. The result of the model calibration for traffic flow is presented in Table 2. The difference between the observed and modeled traffic flow and GEH of all links passed the acceptance target, proposed by the Wisconsin Department of Transport [26]. This result means that simulated traffic volume is close to traffic volume in the field. The result of the model calibration for a maximum queue length is presented in Table 3. The difference between the observed and modeled maximum queue length passed the acceptance target, proposed by Ahmed [27]. This result

Table 2: Results of traffic flow model calibration.

Link	Observed (veh/hr)	Modeled (veh/hr)	Diff. (veh/hr)	GEH	Acceptance target Diff.*	GEH**	Pass/fail
Sreechan-NaMuang intersection							
WB-L	89	85	−4	0.43	Within 100	<5	Pass
WB-T	1,097	1,023	−7%	2.27	Within 15%	<5	Pass
WB-R	148	143	−5	0.41	Within 100	<5	Pass
NB-L	226	217	−9	0.60	Within 100	<5	Pass
NB-T	560	554	−6	0.25	Within 100	<5	Pass
NB-R	257	242	−15	0.95	Within 100	<5	Pass
EB-L	190	201	11	0.79	Within 100	<5	Pass
EB-T	826	797	−4%	1.02	Within 15%	<5	Pass
EB-R	220	208	−12	0.82	Within 100	<5	Pass
SB-L	155	143	−12	0.98	Within 100	<5	Pass
SB-T	717	751	5%	1.25	Within 15%	<5	Pass
SB-R	170	166	−4	0.31	Within 100	<5	Pass
Sreechan-KrangMuang intersection							
WB-L	307	294	−13	0.75	Within 100	<5	Pass
WB-T	797	695	−13%	3.73	Within 15%	<5	Pass
WB-R	267	285	18	1.08	Within 100	<5	Pass
NB-L	125	99	−26	2.46	Within 100	<5	Pass
NB-T	328	341	13	0.71	Within 100	<5	Pass
NB-R	212	224	12	0.81	Within 100	<5	Pass
EB-L	255	247	−8	0.50	Within 100	<5	Pass
EB-T	758	695	−8%	2.34	Within 15%	<5	Pass
EB-R	258	239	−19	1.21	Within 100	<5	Pass
SB-L	444	430	−14	0.67	Within 100	<5	Pass
SB-T	574	589	15	0.62	Within 100	<5	Pass
SB-R	293	282	−11	0.65	Within 100	<5	Pass
Sreechan-RungMuang intersection							
WB-L	122	133	11	0.97	Within 100	<5	Pass
WB-T	992	983	−1%	0.29	Within 15%	<5	Pass
WB-R	41	40	−1	0.16	Within 100	<5	Pass
NB-L	82	81	−1	0.11	Within 100	<5	Pass
NB-T	527	532	5	0.22	Within 100	<5	Pass
NB-R	157	153	−4	0.32	Within 100	<5	Pass
EB-L	69	54	−15	1.91	Within 100	<5	Pass
EB-T	1,046	964	−8%	2.59	Within 15%	<5	Pass
EB-R	70	61	−9	1.11	Within 100	<5	Pass
SB-L	211	199	−12	0.84	Within 100	<5	Pass
SB-T	543	549	6	0.26	Within 100	<5	Pass
SB-R	100	94	−6	0.61	Within 100	<5	Pass

*Diff., hourly link flow of modeled versus observed within 100 veh/h, for flow < 700 veh/h within 15%, and for 700 veh/h < flow < 2,700 veh/h; **GEH statistics < 5; $GEH = \sqrt{(V - C)^2/((V + C)/2)}$, where GEH is GEH statistic; V is simulated traffic flow; C is surveyed traffic flow; [26].

means that maximum queue length of simulated traffic flow is close to maximum queue length in the field. These results imply that the developed traffic microsimulation model could closely simulate traffic condition compared with real-world conditions.

3.2. On-Road Exhaust Emission Models. Nonlinear regression with the exponential form resulted in the best model that passed the t-test with a 95% confidence level and yielded the highest goodness of fit, as presented in Table 4. The results show that the relationships between the emissions of CO_2,

Table 3: Results of the model calibration of the maximum queue length.

Link	Observed (veh)	Modeled (veh)	Diff. (veh)	Acceptance target (Diff.*)	Pass/fail
			Sreechan-*NaMuang intersection*		
WB	30	26	–13%	Within 20%	Pass
NB	20	24	19%	Within 20%	Pass
EB	12	12	0%	Within 20%	Pass
SB	30	34	–13%	Within 20%	Pass
			Sreechan-KrangMuang intersection		
WB	16	13	–19%	Within 20%	Pass
NB	11	10	–9%	Within 20%	Pass
EB	14	12	–14%	Within 20%	Pass
SB	23	21	–9%	Within 20%	Pass
			Sreechan-RungMuang intersection		
WB	16	18	–13%	Within 20%	Pass
NB	17	18	6%	Within 20%	Pass
EB	23	27	17%	Within 20%	Pass
SB	17	20	18%	Within 20%	Pass

*[27].

Table 4: On-road exhaust emission models of motorcycles.

On-road emission rate models	R^2	p values for t-test
LN (ERCO) = 0.101 − 0.002u + 0.449a	0.571	Constant: 0.0000, u: 0.0000, a: 0.0000
LN ($ERCO_2$) = 0.269 + 0.005u − 0.548a	0.961	Constant: 0.0000, u: 0.0000, a: 0.0000
LN (ERHC) = 0.005 − 0.000099u + 0.014a	0.811	Constant: 0.0000, u: 0.0000, a: 0.0000
LN (ERNOx) = −0.001 + 0.000089u − 0.015a	0.931	Constant: 0.0000, u: 0.0000, a: 0.0000

ER: emission rate (g/s), u: instant speed (km/hr), and a: instant acceleration (m/s^2).

HC, and NOx with instantaneous speed and acceleration are very high because their R^2 values are very close to 1. The relationship between CO emissions and instantaneous speed and acceleration is moderate. These values are satisfactory compared with those from a previous study [19].

3.3. On-Road Fuel Consumption Model. The result of the fuel consumption model development is presented in Table 5. The linear regression resulted in the best model that passed the t-test with a 95% confidence level and provided the highest goodness of fit. The relationship between fuel consumption and instantaneous speed is high, as indicated by a coefficient of determination (R^2) close to 1. The fuel consumption rate and the instantaneous speed show a positive correlation, similar to the results from previous studies by Wang et al. [22] and Ahn et al. [20].

3.4. Exclusive Zone for Motorcycle Stopping at Signalized Intersections. The evaluation results of the traffic flow measures of effectiveness as well as the emissions and fuel consumption are presented in Tables 6 and 7. As expected, the proposed measure could improve travel times, delays, and queue lengths in the selected study area. The average travel times for motorcycles, other vehicles, and the total system decreased by 13.7%, 18.9%, and 15.2%, respectively. The average delays for motorcycles, other vehicles, and the total system decreased by 4.8%, 21.3%, and 17.2%, respectively. The average queue length decreased by 22.6%. In terms of emissions, the CO_2 emissions of motorcycles, other vehicles, and the total system decreased by 5.0%, 9.1%, and 7.4%, respectively. The CO emissions of motorcycles, other vehicles, and the total system decreased by 3.3%, 8.7%, and 8.2%, respectively. The HC emissions of motorcycles, other vehicles, and the total system decreased by 1.9%, 8.6%, and 8.4%, respectively. The NOx emissions of motorcycles, other vehicles, and the total system decreased by 2.0%, 8.9%, and 8.7%, respectively. In addition, the fuel consumption of motorcycles, other vehicles, and the total system also decreased by 2.8%, 16.8%, and 14.0%, respectively.

The exclusive zones for motorcycles could improve the traffic flow measures for motorcycles, other vehicles, and the total system and could reduce emissions and fuel consumption compared with those under the existing conditions. This result was caused by the exclusive zone for motorcycles, allowing motorcycles to pass other types of stopping vehicles and waiting for a green light at the front of the queue ahead of other vehicles. When the green period starts, the motorcycles accelerate faster than other vehicles, so they cause less impedance on other traffic conditions. This finding supported previous research in Bangkok, Thailand. May and Montgomery [37] found that the pcu value for motorcycles

Table 5: On-road fuel consumption model of motorcycles.

On-road fuel consumption rate model	R^2	p values for t-test
FR = 0.0041 + 0.004u − 0.277a	0.838	Constant: 0.0000, u: 0.0000, a: 0.0000

FR: fuel consumption rate (ml/s), u: instant speed (km/hr), and a: instant acceleration (m/s^2).

Table 6: Results of the effectiveness of traffic flow measures.

Vehicle type	1. Existing	2. Exclusive motorcycle zone
	Average travel time (s)	
Motorcycles	63.5	54.8 (−13.7%)
Other vehicles	143.1	116.1 (−18.9%)
Total system	125.9	106.7 (−15.2%)
	Average delay (s)	
Motorcycle	50.4	48.0 (−4.8%)
Other vehicles	127.2	100.1 (−21.3%)
Total system	111.7	92.5 (−17.2%)
	Average queue length (vehicles)	
Total system	31	24 (−22.6%)

Table 7: Results of evaluation of emissions and fuel consumption.

Vehicle type	1. Existing	2. Exclusive motorcycle zone
	CO_2 emission (kg)	
Motorcycle	690.1	655.7 (−5.0%)
Other vehicles	932.5	847.2 (−9.1%)
Total system	1,622.6	1,502.9 (−7.4%)
	CO emission (kg)	
Motorcycle	338.7	327.5 (−3.3%)
Other vehicles	2,823.3	2,576.6 (−8.7%)
Total system	3,162.0	2,904.0 (−8.2%)
	HC emission (kg)	
Motorcycle	134.0	131.4 (−1.9%)
Other vehicles	3,484.7	3,184.9 (−8.6%)
Total system	3,618.8	3,316.2 (−8.4%)
	NOx emission (kg)	
Motorcycle	134.2	131.5 (−2.0%)
Other vehicles	3,806.7	3,467.1 (−8.9%)
Total system	3,940.9	3,598.6 (−8.7%)
	Fuel consumption (l)	
Motorcycle	44.60	43.34 (−2.8%)
Other vehicles	177.44	147.56 (−16.8%)
Total system	222.04	190.90 (−14.0%)

crossing the stop line in the first 6 s of effective green time is 0 and that the pcu value for motorcycles crossing the stop line later in the cycle varies from 0.53 to 0.65, depending on the lateral positioning of the motorcycle and its turning movement. In the UK, the pcu value typically applied to motorcycles at signalized intersections is 0.33 [38].

4. Conclusions and Recommendations

This study developed an on-road exhaust emission and fuel consumption model for motorcycle in an Asian developing city and presented its applications for evaluating the traffic management strategy. The onboard measurement system was developed and installed on a motorcycle type that is typical in Asian developing cities. The test vehicle is driven randomly on selected routes in the study area of Khon Kaen City, Thailand, to simultaneously collect on-road speed-time data, exhaust emissions, and fuel consumption per second. These data were applied to develop on-road emission and fuel consumption models. The models were developed with high correlations between the amount of exhaust emissions and fuel consumption and the instantaneous speed and acceleration rate. Developing first on-road exhaust emission and fuel consumption models for motorcycles in Asian developing countries would be useful for the evaluation of measures and strategies to reduce emissions and fuel consumption at the micro level.

The study presented an application of the developed models to evaluate the traffic management strategy for motorcycles through traffic microsimulation. The evaluation results reveal that the proposed measures of the exclusive zone for motorcycle stopping at signalized intersections could improve the level of service in the studied intersections by decreasing travel times, delays, and queue lengths at intersections. Additionally, the fuel consumption and emissions of vehicles traveling through intersections were decreased. This measure could be considered an IMPROVE strategy that is in line with the CUTE matrix. The exclusive zone for motorcycles at signalized intersections should be widely promoted because it is one of the most interesting traffic management strategies to reduce emissions and fuel consumption for motorcycle-dominated traffic. In addition, the case study demonstrated that the developed models could be applied with the traffic microsimulation model to evaluate the traffic measures for encouraging a low-carbon society in Asian developing city.

As recommendations for further studies, the developed onboard measurement system can be further used to collect other on-road driving behaviors by age and engine size of motorcycles as well as gender and weight of drivers. They might affect differently fuel consumption and emissions. The collecting data can be applied to develop the motorcycle eco-driving cycles. These eco-driving cycles will be useful for the development of an eco-driving assistance system for motorcyclists for reducing fuel consumption and emissions. In addition, the developed on-road and fuel consumption models will be further applied to evaluate the dynamic eco-driving for motorcycles driven along a signalized corridor [39] and other traffic management plans, such as the design of traffic signalized controls at intersections or the design of a coordination control of signalized intersections for minimizing emissions and fuel consumption in developing countries.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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