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ESTIMATING THE GREENHOUSE GAS EMISSION FACTOR OF MOTORCYCLES UNDER REAL-WORLD DRIVING CONDITIONS IN HANOI: A CASE STUDY

Nguyen Thi Yen Lien, Than Thi Hai Yen*

University of Transport and Communications, No 3 Cau Giay Street, Hanoi, Vietnam

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* *Corresponding author*
Email: thyen@utc.edu.vn

Abstract. The lack of country-specific greenhouse gas (GHG) emission factors vehicles in Vietnam makes the emissions inventory in the transport sector more difficult. This study developed the country-specific GHG emission factor in terms of CO_2 equivalent for motorcycles (MCs) in Hanoi to overcome the above impediment. The real-world driving data, instantaneous speed versus time, were collected on the 30 road routes in Hanoi using a GPS device. A filtering process of nine-step was designed to repair misleading speed values and denoise signals before entering the International Vehicle Emissions (IVE) model. The typical GHG emission factor for the MC fleet in Hanoi was approximately 90.83 g/km. This study also found a remarkable difference in the MC's specific power-related bins distribution between the real-world driving characteristics of the MC in Hanoi and the ones of the World Motorcycle Test Cycle. This contributes to reconfirming the necessity of developing the GHG emission factor based on the very real-world driving data of Vietnam.

Keywords: emission factor, GHG, GPS, motorcycle, IVE.

1. INTRODUCTION

Local air pollution and greenhouse gas (GHG) emissions are currently posing an urgent problem for all countries in the world. Among anthropogenic causes, the transport sector has been identified as one of the main contributors to this predicament. In Vietnam, the transport sector is responsible for around 18% of GHG emissions, and these emissions are continually rising along with the skyrocketing number of vehicles on the road, especially motorcycles (MC)

[1]. Until 2020, the total number of MCs in Vietnam is about 65.2 million, accounting for up to 92% of all road vehicles [2]. In addition, in terms of new sales, Vietnam's MC market is located second in Asia and fourth in the world behind India, China, and Indonesia [3]. As an unexpected result, the MC fleet has had a considerable impact on the deteriorating air quality in Vietnam and the speeding up of global climate change. Facing this reality, the Vietnamese government has set defined goals for lowering GHG emissions in all sectors to achieve the target of greenhouse gas emission reduction by 2030 of 146.3 $MtCO_2eq$ (unconditional contribution) and 403.7 $MtCO_2eq$ (conditional contribution), in which the transport sector is one of the important sectors [4]. This leads to a need for the emission inventory of MCs to serve as a scientific basis for integrated air quality management in Vietnam.

Emission factor (EF) is a valuable tool for estimating the number of pollutants released from a specific source; hence, it is widely used in the emission inventory. Currently, the vehicle's EF database is quite abundant since they are provided by international organizations and other countries. However, EF is influenced by many factors related to the characteristics of each country including the vehicle's type and age, air pollution control technologies, the fuel's type and quality, inspection and maintenance (I/M) conditions, ambient air conditions, and the vehicle's operating conditions. Therefore, applying EFs developed by other nations could not capture the vehicle's emission characteristics in Vietnam fully. In other words, the level of uncertainty in national emission inventory results can be lower by the use of country-specific emission factors (CSEFs) rather than values derived from other countries [5]. Additionally, the vehicle's emissions on the road are always higher than the ones determined in the vehicle type approval [6]. Therefore, it is necessary to develop the CSEFs based on the country's real-world operation data.

In Vietnam, there are several earlier studies relating to developing CSEFs for road vehicles. For instance, Tung *et al.* (2011) determined the CSEFs for MCs and light-duty vehicles based on the typical driving cycles and the emissions measurement on the chassis dynamometer; Kim Oanh *et al.* (2012) estimated the CSEFs of MC in Hanoi using the real-world driving data and IVE model; Nghiem *et al.* (2019) developed the bus's CSEFs based on the typical driving cycle of the bus in Hanoi and the bus's engine emissions measurement on the engine dynamometer. However, all previous studies did not focus on the vehicle's GHG emission factor. Although the GHG emission factor can be calculated based on the EF of other pollutants, these pollutants were not fully included in the previous studies even in legal documents related to emission inventory guidelines of the Ministry of Natural Resources and Environment (MONRE) [10]. This approach, therefore, becomes impossible in the current context of Vietnam. Although most recently MONRE published a list of EFs for the inventory of GHG emissions [11], these EFs are the default EFs provided by Intergovernmental Panel on Climate Change (IPCC) to support the emissions inventory in nations in case of the absence of CSEFs in those countries. By the use of the default EFs, the accuracy of obtained emission inventory results will be lowest (Tier 1 level) [12].

In light of the aforementioned elements, this study aims to produce the GHG emission factor for the MC in Hanoi based on its real-world driving characteristics. Using the country-specific GHG emission factor will improve the accuracy of GHG emission inventory results to reach Tier 3 [12].

2. METHODOLOGY

The overall methodology utilized to determine the GHG emission factor of MCs in Hanoi is given in Fig.1.

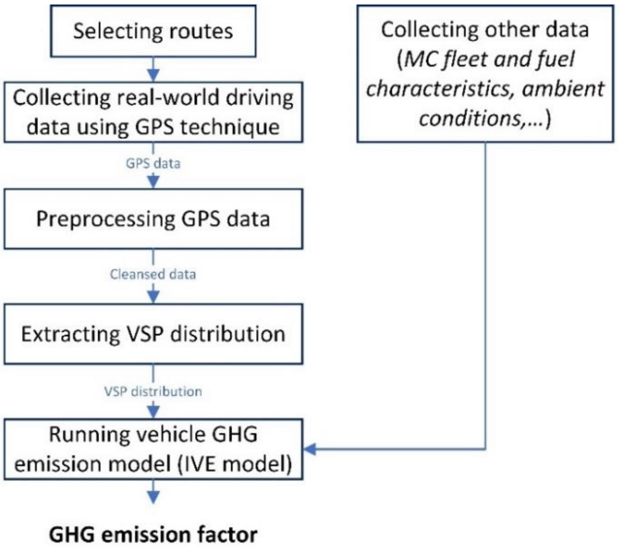

Figure 1. The procedure for determining the GHG emission factor of MC in Hanoi.

2.1. Selecting routes

The routes are often selected based on the researchers' judgment, such as relying on road type, home-to-work trips, the difference in population density, and so on [13]. In this study, routes need to be selected so that they can capture fully the real-world driving characteristics of MCs in Hanoi. Therefore, 30 routes consisting of both central and suburban routes were selected to achieve the research objective (see Fig. 2).

Figure 2. Map of selected routes, built based on [14].

2.2. Collecting real-world driving data

The on-road driving characteristic of the MC in Hanoi was collected on weekdays and weekends at both off-peak and rush (6:30-8:30; 10:30-12:00; 16:30-19:00) hours. Furthermore, only one person put driving the test MC on all chosen routes into effect to avoid the impact of driver's behavior. A GPS device (Garmin 65s) with the 1Hz position update rate was utilized during the entire data collection process (see Fig. 3).

Figure 3. GPS device (Garmin 65s) [15].

In addition, this study also gathered real-world driving data by the use of the data logger concurrently with the GPS device on the test MC on one route as a foundation to evaluate the reliability of the GPS device used.

2.3. Preprocessing GPS data

The GPS data may include random errors related to sudden signal loss, misleading or outlying data points, and speed drifting [16, 17]. Therefore, it is necessary to minimize these errors before using the GPS data for extracting the VSP distribution in the next step. In this study, a filter process was designed in increasing complexity order of nine steps as presented in Fig. 4.

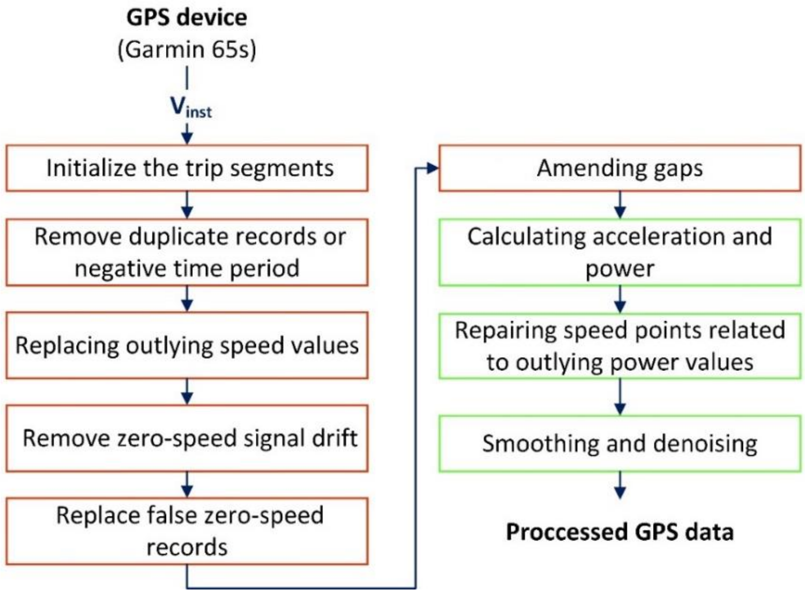

Figure 4. Flowchart of GPS data preprocessing.

The operation principle of steps 1 to 6 highlighted in red color was described in our previous study [18]. The remaining misleading speed values that cause the outlying acceleration points will be continuously removed by checking the errors in the second dataset of instantaneous engine power due to the availability of limited engine power data for MC. The operation principle of this further processing stage, consisting of steps highlighted in green color, was also described in our previous study [19].

All steps of the data filtration procedure shown in Fig. 4 were carried out on the Matlab2018a software.

2.4. Collecting other data

Additional data includes MC fleet features, fuel characteristics, and meteorological data (such as average annual temperature and humidity). The gasoline quality was collected from Petrolimex while the meteorological data was taken from the meteorological website http://www.nchmf.gov.vn. The MC fleet features were inherited from the earlier relevant studies consisting of Kim Oanh *et al.* (2012), Dung *et al.* (2015), and Duc *et al.* (2019).

2.5. Running vehicle emission model

In this study, IVE (International Vehicle Emissions) model developed by the US Environmental Protection Agency (US.EPA) was utilized to simulate the vehicle's GHG emissions based on the processed GPS data. This model is specifically designed for developing countries to estimate road vehicle emissions and it is also extensively utilized in relevant studies. For instance, Trang *et al.* (2015) utilized the IVE model to estimate the pollutant emissions for taxis, buses, and personal cars; Lien and Dung (2018) estimated the potential health benefit associated with climate change mitigation measures for the bus in Hanoi, Vietnam based on the IVE model; Ghaffarpasand *et al.* (2021) used the IVE model to estimate the MC fleet's emissions in Iran. The fact is that the accuracy of the IVE model was evaluated by Guo *et al.* (2007) where a good agreement between the IVE-based simulated and measured EFs (all the correlation coefficients were above 0.8) was recognized. Therefore, the IVE model was used in this study.

In the IVE model, the real-world driving characteristic is entered through the frequency distribution of 60 bins that are defined based on the vehicle-specific power (VSP) and engine stress [26]. The preprocessed GPS data, therefore, was used to calculate VSP and engine stress parameters according to Eq. (1) and Eq. (2), respectively.

For motorcycles, VSP can be calculated based on the following equation [26]:

$$VSP = v \times (1.1 \times a + 9.81 \times a\,tan(sin(G)) + 0.132) + 3.02 \times 10^{-4} v^3 \qquad (1)$$

Where: VSP is vehicle-specific power (kW/ton); v is vehicle instantaneous speed (m/s); a is vehicle instantaneous acceleration (m/s^2); G is the grade of the road (radian) (in case of Hanoi, G ~ 0).

Engine stress is calculated using the following equation [26]:

$$\text{ES (unitless)} = \text{RPMIndex} + (0.08\ \text{ton/kW}) \times \text{PreaveragePower} \qquad (2)$$

where: PreaveragePower = Average ($VSP_{t\text{-}5\ to\ t\text{-}25sec}$) (kW/ton);

RPMIndex = $Speed_{t=0}$/SpeedDivider (unitless).

2.6. Calculating greenhouse gas emission factor

EFs of greenhouse gases determined based on the IVE model will be used to calculate the representative GHG emission factor in terms of CO_2eq as follows [12]:

$$EF_{CO2eq} = \sum_{i=1}^{n} EF_i \times GWP_i \quad (3)$$

Where: EF_{CO2eq} is CO_2eq emission factor (g/km), EF_i is the emission factor of GHG i (consisting of CO_2, NO_2 and CH_4 [12]) (g/km), GWP_i denotes the global warming potential of GHG i (considered for different time intervals, usually for 20 years or 100 years [27]).

3. RESULTS AND DISCUSSION

3.1. Pre-processing results

The pre-processing results for the real-world driving dataset extracted from the GPS device are shown in Table 1.

Table 1. Data pre-processing results.

Errors	**Error ratio**	
	This study (%) (using Garmin 65s)	**Comparison with another study using a data logger [19]**
Outlying speed	0	1.6
Outlying power or acceleration relating to misleading speed	0	0.2
Gaps	1.9	0
Errors related to time	2.8	N/A
Zero speed drift	0	N/A
False zero speed	1.2	N/A
Total	**5.9**	**1.8**

Note: N/A denotes the error category that does not appear in the corresponding data type.

As can be seen from Table 1, on average, the percentage of the original data points processed in different steps of the filtration process is approximately 5.9%. Among these errors, the time-related error caused by duplicate records accounts for the largest ratio (2.8%), followed closely by signal gap-related error (1.9%) and error relating to false zero-speed (1.2%). In comparison with the data that was collected using the data logger, a device is connected directly to the vehicle wheel to determine the vehicle's instantaneous speed based on its wheel rotation speed, it was shown that the error ratio in the GPS data is 3.2 times higher than the logging data. However, there is a strong similarity between the pre-processed GPS and pre-processed logging data since the average difference percentage between the two datasets is only up to 4.1% (see Fig. 5). In which, the reliability of logging data has been validated by comparing with the speed profile measured on the motorcycle chassis dynamometer as described in our previous [19]. In addition, as shown in Fig. 5, the profiles of the GPS data and the logging data are very similar.

These imply that the combination of the designed filter and GPS device could capture well the real-world driving characteristic of MC in Hanoi.

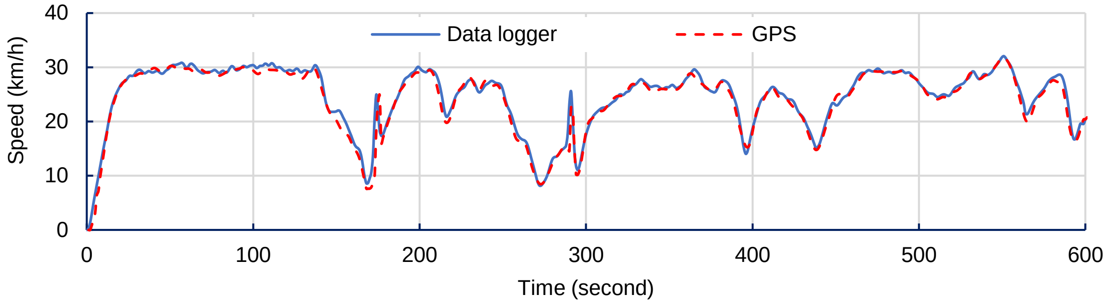

Figure 5. Comparison between the GPS data and the logging data (data after pre-processing).

3.2. Bins distribution

The pre-processed GPS data was used to determine the distribution of bins that will be used as the input parameter related to the real-world driving characteristics in the IVE model. Fig. 6 compares the bins distribution of the World Motorcycle Test Cycle (WMTC) with the bins distribution of the real-world driving data of the MC in Hanoi.

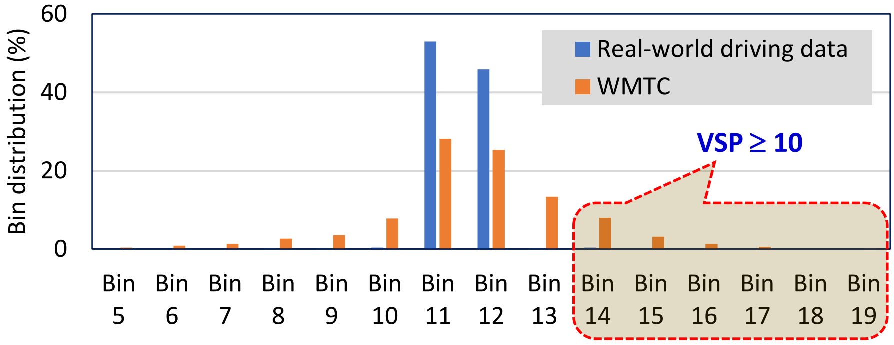

Figure 6. Comparison of bins distribution between the real-world driving data and WTMC.

(Note: Empty bins are not shown in the figure above)

As can be seen in Fig. 6, the real-world driving characteristic of MC in Hanoi only concentrates in the range of Bin 8 to Bin 14 corresponding to the VSP $\in$ [-12.5; 13.6] interval. Among this region, the distribution of the real-world driving data in Bin 11 reaches the highest ratio, approximately 53%. The second highest distribution was found at Bin 12 with a distribution ratio of 46%. The fact is that both Bin 11 and Bin 12 contain the zero or very low VSP region. Therefore, this finding is consistent with the study of Dung *et al.* (2015) for the MC fleet in Ho Chi Minh City, Vietnam. This can be explained by the frequent traffic congestion in Vietnam's major cities, including Hanoi and Ho Chi Minh. In addition, as shown in Fig. 6, the bin distribution of MC in Hanoi is very different from the distribution of the bin in WMTC, the average percentage difference reaches 162.5%. The fact is that numerous studies have found a close correlation between VSP and the pollutant emissions of the vehicle. In the VSP range greater than 10kW/ton, the higher the VSP, the lower the vehicle emission [28, 29]. These imply that the actual MC emission in Hanoi might be higher than the MC emission as measured by WMTC. In light of the aforementioned factors, it has reaffirmed the necessity of developing the GHG emission factor based on the real-world driving data of Vietnam.

3.3. GHG emission factors

By running the IVE model based on the collected data, the GHG emission factors of the MC in Hanoi were determined as given in Table 2. In addition, the emission factors of a number of other pollutants were also included in Table 2 as a basis for comparing and evaluating the reliability of the acquired results.

Table 2. Pollutant emission factors of MC in Hanoi.

Pollutants	EFs in this study (g/km)	Comparison with other studies	
		EF (g/km)	Explanation
GHGs			
CO_2	61.31	50.26	Tung *et al.* (2011) for Honda Lead 125cc, vehicle age of 3 years. This result has also been included in the legal document related to the guidance of emissions inventory in Vietnam [10].
		62.92	Kim Oanh *et al.* (2012) for the MC fleet in Hanoi
CH_4	0.41	0.43	
CO_{2eq} (for 20 years)	**90.83**	**-**	
Other pollutants			
NO_x	0.15	0.11	Tung *et al.* (2011) for Honda Lead 125cc, vehicle age of 3 years; measuring emissions on the chassis dynamometer
		0.21	Kim Oanh *et al.* (2012) for the MC fleet in Hanoi; using the IVE model
VOC	2.07	1.99	
SO_2	0.01	0.01	
PM	0.10	0.12	

Table 2 shows that the results obtained in this study are within the range of ones published in the previous studies. However, the majority of EFs obtained in this study are higher than those published by Tung *et al.* (2011) but smaller than those given in the study of Kim Oanh *et al.* (2012). This is reasonable because EFs from Tung *et al.* (2011) that were mentioned above are for a new MC (vehicle age of 3 years), but this study calculated the average EFs of the MC fleet, which includes both new and old MCs. In addition, the real-world driving characteristics of the MC in Hanoi have also changed over time due to the Vietnam government's ongoing efforts in upgrading the transport infrastructure as demonstrated in [30]. As a result, EFs obtained in this study are smaller than those published by Kim Oanh *et al.* (2012). In other words, the EFs determined in this study are reliable. Therefore, the CO_2eq emission factor of the MC in Hanoi being 90.83 g/km which was calculated based on the GHGs emission factors is also highly reliable.

4. CONCLUSIONS

The real-world driving data of the MCs in Hanoi was collected using a GPS device over 30 routes in Hanoi. The collected data were processed to remove the random errors and denoise by a designed filter with nine steps. The percentage of misleading speed data points detected and repaired is approximately 5.9%. After that, the processed GPS data was utilized to calculate the frequency distribution into 60 bins based on VSP and engine stress. The real-world driving characteristics of Hanoi's MCs mainly concentrate in the low VSP region (Bin 11 and Bin 12). This implies that the actual emission of the MCs in Hanoi could be significantly higher than the ones measured according to World Motorcycle Test Cycle, which focuses primarily on the high VSP region. Hence, future research investigations are recommended to determine the emission factors based on the real-world driving features of the very region on which their research is focused instead of using the driving characteristics collected from other regions or the standard test cycles. The GHG emission factor in terms of CO_2eq, approximately 90.83 g/km, was determined based on the actual bin distribution and the MC fleet characteristics in Hanoi. The achieved GHG emission factor is a very good basis for improving the quality of GHG emission inventory as well as integrated air quality management in Vietnam.

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