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Comparison of Real-Life Operating Fuel Consumption of Two-Wheelers Fueled by Bio-Ethanol and Gasoline, a Simulation Approach

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Abstract

Research on developing a simulation model to determine fuel consumption (FC) of motorcycles using bio-ethanol and gasoline based on real-world operational data. A computational model was developed using the AVL-Cruise tool to simulate FC. The accuracy of the model was validated using experimental data from a chassis dynamometer test under the WMTC (World Motorcycle Test Cycle). The results show that the model can closely replicate real-world FC. When comparing the simulated and experimental FC data, the coefficient of determination R^2 was 0.8778, the root mean square error (RMSE) was 28.70 mg/s, and the root mean square percentage error (RMSPE) was 22.89%. Additionally, 67.27% of instant FC data points had deviations within 20%. The model was then used to simulate FC for motorcycles using gasoline and bio-ethanol under four-speed profiles collected from four representative urban areas in Hanoi. The simulation results indicate that when using bio-ethanol, FC was increased by around 13.12%, while energy consumption (EC) was decreased by 24.84% due to differences in the properties of the two fuels. This confirms the advantages of bio-ethanol when used in internal combustion engines.

Keywords: Bio-ethanol, motorcycles, fuel consumption, AVL-Cruise.

1. Introduction

Many nations are implementing major initiatives to conserve energy and cut greenhouse gas emissions in the transportation sector, driven by concerns over climate change and the depletion of fossil fuels. Due to its substantial energy consumption (EC), the transport industry has become a focal point for policymakers, automobile manufacturers, and consumers. In Vietnam, the number of two-wheelers (2Ws) has been growing rapidly, particularly in major urban areas. In 2018, Hanoi had nearly 6 million 2Ws and 600,000 cars, with annual growth rates of 9% and 13.7%, respectively [1]. The swift expansion of the motorcycle fleet has led to increased fuel consumption (FC) and worsening air quality in the city. In Hanoi, the 2Ws fleet equipped with internal combustion engines accounted for 15% of particulate matter (PM10) emitted by buses [2], while motorcycles, vans, and trucks were responsible for 36% of CO_2 emissions and over 90% of hazardous air pollutants [3].

The depletion of fossil fuels and environmental pollution are major concerns in developing countries due to the increasing number of vehicles and the expansion of industrial sectors. A promising approach to addressing these issues is the adoption of green energy, where alternative fuels have been extensively researched and applied worldwide. Many studies have focused on replacing fossil fuels in transportation and industry with alternative energy sources. For instance, bio-ethanol, liquefied petroleum gas, compressed natural gas, and biodiesel have been introduced and utilized in light-duty vehicles and motorcycles. Among them, bio-ethanol is widely employed as a primary fuel or fuel additive to reduce dependence on conventional petroleum-based fuels in various countries [4].

Numerous experimental and theoretical investigations have been conducted globally on the application of bio-ethanol in internal combustion engines. These studies have provided valuable insights that have contributed to the widespread adoption of bio-ethanol and the advancement of renewable energy sources [5]. Key characteristics of bio-ethanol have been highlighted in recent research [6]. One of the most notable properties is its lower heating value (LHV), which represents the amount of energy released during combustion. Compared to gasoline, bio-ethanol has a significantly lower LHV, with values of 44 MJ/kg for pure gasoline and 26 MJ/kg for bio-ethanol. Another important property is the amount of intake air required to achieve complete combustion. Since bio-ethanol contains about 34% oxygen by weight, it demands less air for burning than gasoline, 9.0 kg for bio-ethanol compared to 14.7 kg for pure gasoline. Thus, theoretically, when ensuring the same air-fuel ratio, the amount of bio-ethanol fuel is approximately 1.6 times

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higher than that of gasoline, based on preliminary calculations while disregarding differences in the properties of the two fuels [7]. In reality, the actual bio-ethanol FC under the same operating conditions as a gasoline-fueled engine may not strictly follow this ratio. Some differences in properties between the two types of fuel include the RON (Research Octane Number), heat of vaporization, and vapor pressure. These differences can affect the operation of a bio-ethanol-fueled engine in certain conditions, such as acceleration, deceleration, idling, and cold start [7].

Vietnamese researchers have been exploring the potential of bio-ethanol as an alternative fuel for spark ignition (SI) engine vehicles. The use of bio-ethanol in transportation not only reduces the reliance on fossil fuels but also supports the growth of the agricultural sector. Domestic studies have examined the performance and emission characteristics of SI engines running on bio-ethanol-gasoline blends, as well as the compatibility of fuel system components with these blends. Previous studies have primarily been conducted in laboratory settings, under steady-state conditions or standardized test cycles, with limited diversity in traffic scenarios. Therefore, evaluating the FC of engines in general, and bio-ethanol engines in particular, under real driving conditions would be more meaningful. Moreover, there is a lack of research on the implementation of pure bio-ethanol in currently used vehicles.

Therefore, estimating FC from motorcycle fleets in Vietnam, particularly in Hanoi, remains essential. Estimating FC in the transportation sector plays a crucial role in understanding energy efficiency and overall pollution levels. Although motorcycles continue to be the primary mode of transport in many developing countries, including Vietnam, research on FC modelling remains limited. For this reason, our study aimed to develop a simulation model for a 2W fueled with bio-ethanol and gasoline, and validate it using real-world driving data.

To construct an instantaneous FC simulation model, this study utilized the advanced AVL-Cruise simulation tool. This tool enables the determination of instantaneous FC (FC_{inst}) and fuel consumption per kilometer (FC_{km}) if actual speed profiles from real-world driving conditions are obtained. In this study, a data logger device was used to collect second-by-second operational data of motorcycles, including FC_{inst} and instantaneous speed (V_{inst}). The model employs V_{inst} as an input variable, while FC_{inst} is utilized for validation and evaluation. The FC of vehicles using bio-ethanol and gasoline is simulated and evaluated under real-world operating conditions.

2. Material and Procedure

2.1. Study Procedure

The framework for modelling real-world motorcycle FC is illustrated in Fig. 1. The red colour box marks the experimental setup phase, while a prior study provided insights into the on-road data collection process [8].

The research process consists of four steps. The 1st step begins with collecting the technical specifications of the test subject to develop the model. In the 2nd step, during the model construction, an important task is to validate it using laboratory data under a specific operating mode. Here, the authors assess the model's accuracy by utilizing measurement data obtained when the vehicle follows the WMTC (World Motorcycle Test Cycle). Once the model is developed, the authors use it to simulate FC when using bio-ethanol and gasoline based on several real-world vehicle speed profiles. The final step involves analyzing and evaluating instantaneous and average FC and EC when the vehicle operates on bio-ethanol and gasoline.

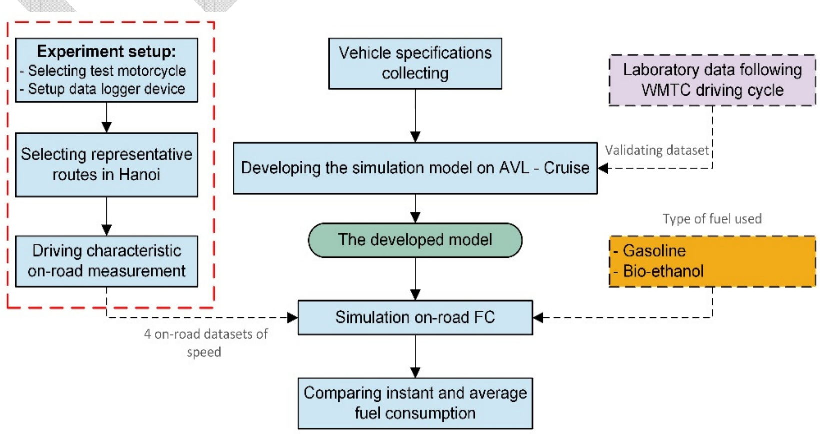

Fig. 1. The study procedure

2.2. Instantaneous Vehicle Speed and Fuel Consumption Measurement

A customized data logger was developed to capture real-world motorcycle performance, recording parameters such as V_{inst} and FC_{inst}. The system uses sensor signals to measure wheel rotations for speed tracking and injection pulses for FC estimation. A bluetooth feature enables real-time data viewing and storing on a portable device during rides. The data collection approach was detailed in Duc *et al.*, [8]. Fig. 2 presents the test 2W and the data logger in a testing condition for model validation (inherited from the previous study [9]).

2.3. On-Road Driving Characteristics Collecting

Le *et al.* [10] identified Hanoi's inner city as comprising several sections, including the old town, historic streets, the traditional core, and newly developed districts. Based on this, four routes covering these four zones were selected for real-world driving data collection, as shown in Fig. 3 (inherited from the previous study) [9].

The four selected roads/streets include route 1 (new region), route 2 (old inner city), route 3 (old street), and route 4 (old town). The instantaneous speed data collected on these four streets is used as input for a simulation to evaluate the FC of vehicles using bio-ethanol or gasoline. To maintain consistency and eliminate variations in driving behavior, all on-road measurements were carried out by a single driver.

2.4. Data Pre-Processing

To improve data reliability before modelling, the collected route datasets were processed to eliminate noise and minimize random errors [11]. A six-step filtering framework was employed: (1) Detecting and adjusting abnormal speed values; (2) Addressing missing data; (3) Computing acceleration and power; (4) Correcting misleading speed records; (5) Smoothing variations and filtering noise; and (6) The data processing procedure is detailed in the study by Duc *et al.*, [8]

2.5. Test Motorcycle

For this study, a Vespa Liberty 3Vie motorcycle, equipped with fuel injection and a three-way catalytic converter, was selected. The detailed specifications of the test vehicle are listed in Table 1.

2.6. Model Development

The motorcycle model was developed using AVL-Cruise, as shown in Fig. 4, incorporating real-world specifications and detailed engine characteristics to ensure accurate simulation results. The constructed model consists of several essential components, including the engine element, wheels, transmission, and braking system, all of which play a crucial role in replicating the real vehicle's performance.

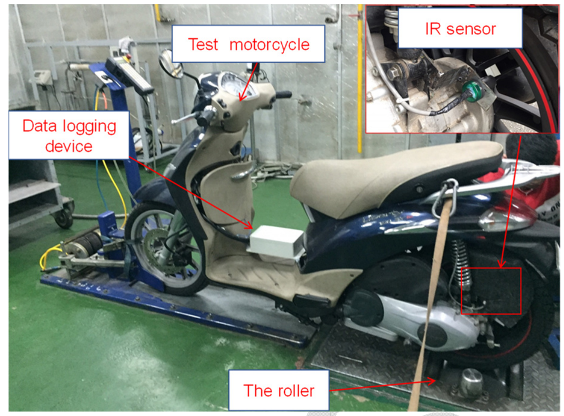

Fig. 2. The test 2Ws on the motorcycle chassis dynamometer

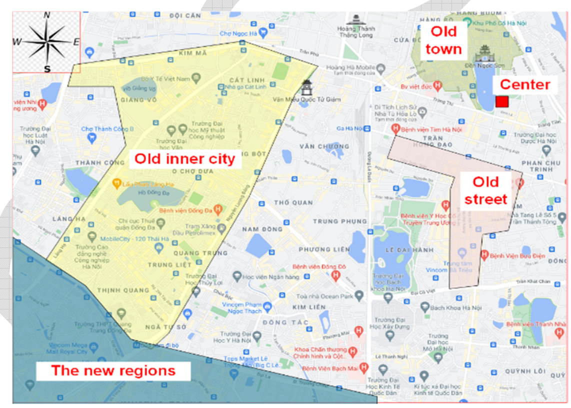

Fig. 3. The sections for data collection

Table 1. Specifications of the test 2Ws

Item	Technical parameters	Unit
Branch and	Piaggio Liberty 3Vie	-
Engine	Single cylinder, 4 strokes, overhead camshaft, 3 valves, spark ignition	-
Model year	2013	-
Mileage	~ 20,000	km
Displacement	149	cm^3
Bore x Stroke	62.2 × 48.6	mm
Compression	11.1:1	-
Max power	8.60/8000	kW/rpm
Max torque	11.20/ 6250	Nm/rpm
Fuel system	Port fuel injection	-
Transmission system	Continuously Variable Transmission	-
After-treatment	Three-way catalyst	-

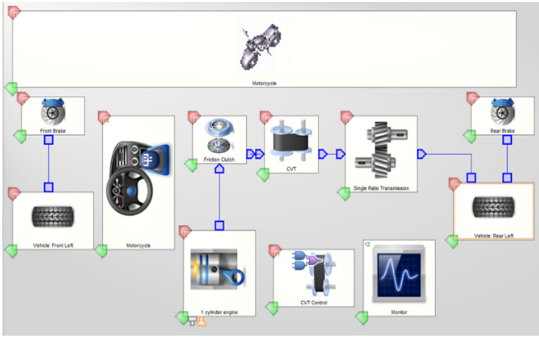

Fig. 4. Developed model of 2Ws in AVL-Cruise

Additionally, the model integrates key powertrain parameters, torque characteristics, and aerodynamic properties to enhance its fidelity. One of the most critical aspects of the model is the incorporation of the engine map, which defines fuel consumption and power output under varying operating conditions. This engine map allows for a precise representation of real-world performance, enabling more reliable simulations of fuel consumption and dynamic responses. Furthermore, factors such as vehicle weight, rolling resistance, and drag coefficients were also taken into account to improve the model's predictive accuracy. By including these elements, the motorcycle model provides a robust platform for analyzing various driving scenarios and optimizing fuel efficiency under different operating conditions. Some coefficients and parameters will be adjusted after validating the model by comparing experimental and simulation results in order to obtain the best-fitting model.

2.7. Model Evaluation

A chassis dynamometer test, conducted under the WMTC driving cycle, was used to validate the model. FC_{inst} from experiments was analyzed and compared with simulation outcomes.

To assess model accuracy, the study employed three evaluation metrics: root mean square error (*RMSE*), root mean squared percentage error (*RMSPE*), and determination coefficient (R^2) as follows:

$$RMSE = \sqrt{\sum_{i=1}^{n} \frac{(m_i - s_i)^2}{n}} \quad (1)$$

$$RMSPE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left\{\left(\frac{m_i - s_i}{m_i}\right) \times 100\%\right\}^2} \quad (2)$$

$$R = \frac{n\sum_{i=1}^{n} m_i s_i - \sum_{i=1}^{n} m_i \sum_{i=1}^{n} s_i}{\sqrt{n\sum_{i=1}^{n} m_i^2 - (\sum_{i=1}^{n} m_i)^2}\sqrt{n\sum_{i=1}^{n} s_i^2 - (\sum_{i=1}^{n} s_i)^2}} \quad (3)$$

where: n is the number of data points in the collection, m_i, and s_i are the measured and simulated FC_{inst} values at data point number i.

Based on the V_{inst} and FC_{inst}, the average FC in units of l/100km is calculated as:

$$FC_{km} = 100 \times \frac{\sum_{i=1}^{n} FC_{inst,i}}{\sum_{i=1}^{n} \frac{V_{inst,i}}{3600}} \times \frac{1}{\rho_{fuel}} \quad (4)$$

where: FC_{km} denotes the FC per unit of travelled distance (g/km), $FC_{inst,i}$ is the instantaneous FC at the time i (g/s), $V_{inst,i}$ is the vehicle speed at the time i (km/h), ρ_{fuel} is fuel density (kg/m^3), and n is the total data points.

The plausible range of metrics and model criticism is: High Accuracy (<10%), Good (10-20%), Reasonable (20-50%), and Inaccurate (>50%) [12].

3. Results and Discussion

3.1. Model Validation Results

The accuracy of the model was assessed by comparing its simulated FC_{inst} values with experimental results obtained from the WMTC transient driving cycle, in which the test motorcycle was fueled with gasoline. As illustrated in Fig. 5, the model's predictions closely aligned with the observed laboratory data over 600 seconds, demonstrating its effectiveness in capturing real-world FC patterns.

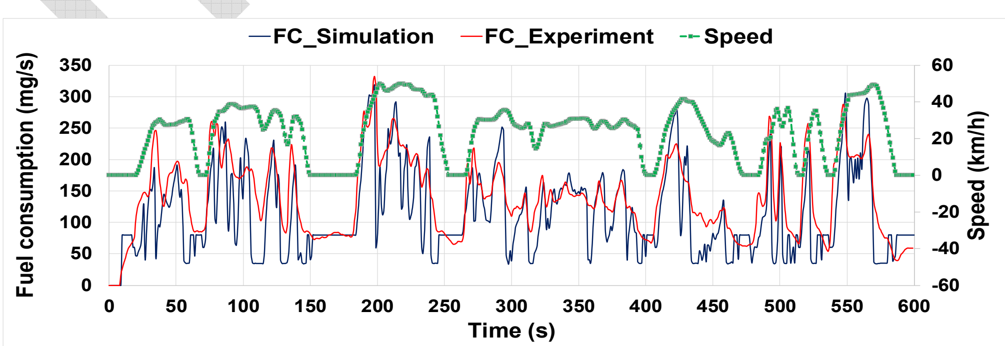

Fig. 5. Measured and simulated FC_{inst} as a function of time following the WMTC driving cycle

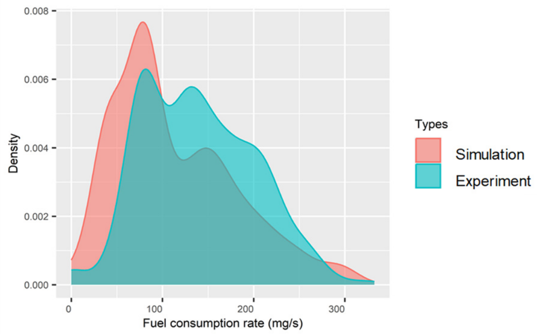

Fig. 6. Frequency distribution chart of measured and simulated FC_{inst} following the WMTC driving cycle

The evaluation metrics further validated the model's performance, yielding an *RMSE* of 28.79 mg/s, an *RMSPE* of 22.89%, and a coefficient of determination of 0.8778, indicating a strong correlation between the simulated and actual data. Furthermore, a detailed analysis of the dataset revealed that 67.27% of the FC_{inst} values exhibited relative deviations within a 20% range from the experimental results, reinforcing the model's reliability in transient driving conditions. These findings suggest that the developed model can effectively replicate real-world fuel consumption dynamics with a reasonable level of accuracy.

The predictive capability of the models can be effectively evaluated by analyzing the distribution chart of FC_{inst} values, as presented in Fig. 6.

It is evident that the distribution of the measured FC_{inst} values obtained from the WMTC cycle closely aligns with the FC_{inst} distribution derived from the simulated data. The degree of overlap between these two distributions reaches an impressive 80.23%, highlighting the model's ability to capture real-world FC behavior with high accuracy. This high overlap rate suggests that the model is capable of effectively replicating transient FC patterns under varying driving conditions, further reinforcing its reliability. Moreover, the consistency between the simulated and experimental FC_{inst} distributions suggests that the model performs well in capturing both the FC_{km} trends and the variations observed in real-world scenarios. This validation aligns with the model evaluation criteria established by Le *et al.* [12], which set benchmarks for assessing the accuracy of FC simulations. Furthermore, the strong agreement between the distributions implies that the model can be confidently used for further studies related to optimizing fuel efficiency, evaluating alternative fuels, and improving vehicle powertrain configurations. These findings demonstrate the robustness of the simulation approach and its potential applicability in various research and development contexts.

Fig. 7 illustrates the correlation between FC_{inst} obtained by simulation and experiment overall and across different operational phases, including acceleration, deceleration, and cruising. The R^2 values for each driving mode, the corresponding evaluation metrics were as follows: during acceleration, *RMSE* was 44.17 mg/s, *RMSPE* was 26.01%, and R^2 was 0.768; for deceleration, *RMSE* reached 27.25 mg/s, *RMSPE* was 22.70%, and R^2 was 0.743; and under cruise conditions, *RMSE* was 15.58 mg/s, *RMSPE* was 19.97%, and R^2 was 0.898.

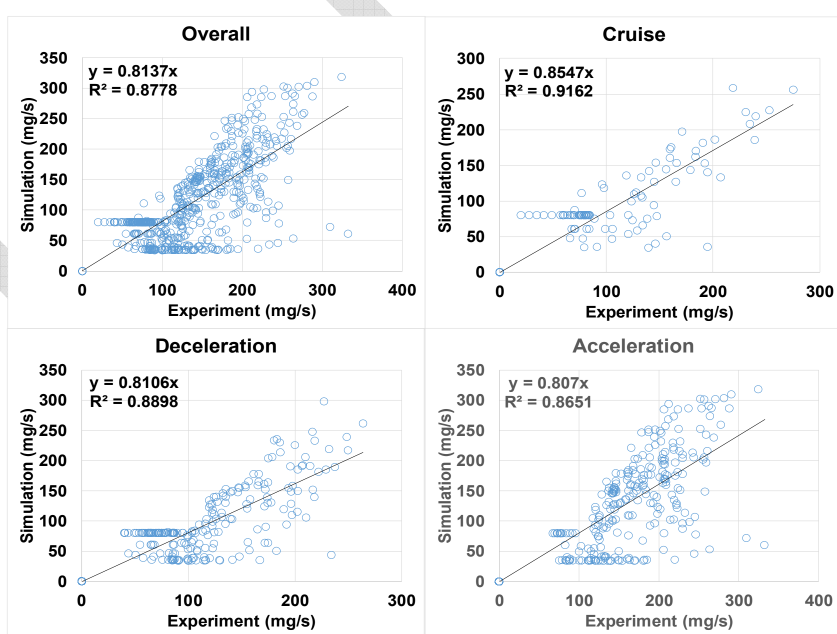

Fig. 7. The correlation between measured and simulated FC_{inst} following the WMTC driving cycle at different driving modes

In addition, the accuracy of the model is also evaluated based on average fuel consumption. Following (4), the estimated and actual FC_{km} values for a full driving cycle were 2.68 l/100 km and 2.81 l/100 km, respectively, resulting in a 4.62% relative deviation. Thus, it can be seen that the model can provide relatively accurate fuel consumption per kilometer results, as the deviation is less than 5%.

3.2. Modeling FC_{inst} of 2Ws Based on on-Road Driving Parameters with Bio-Ethanol and Gasoline

After development, the model was utilized to estimate FC_{inst} using four-speed datasets collected from different routes within Hanoi's central area. Fig. 8 illustrates the simulated FC_{inst} profiles in relation to V_{inst} over time. A strong correlation can be observed between FC_{inst} and vehicle speed, even during sudden acceleration and deceleration phases. This indicates that the model has a good capability to simulate transitional driving conditions. Additionally, a general trend evident in the graph is that bio-ethanol fuel tends to exhibit a higher increase in consumption compared to gasoline across various operating conditions, including idle mode. This result aligns with previous similar studies [4].

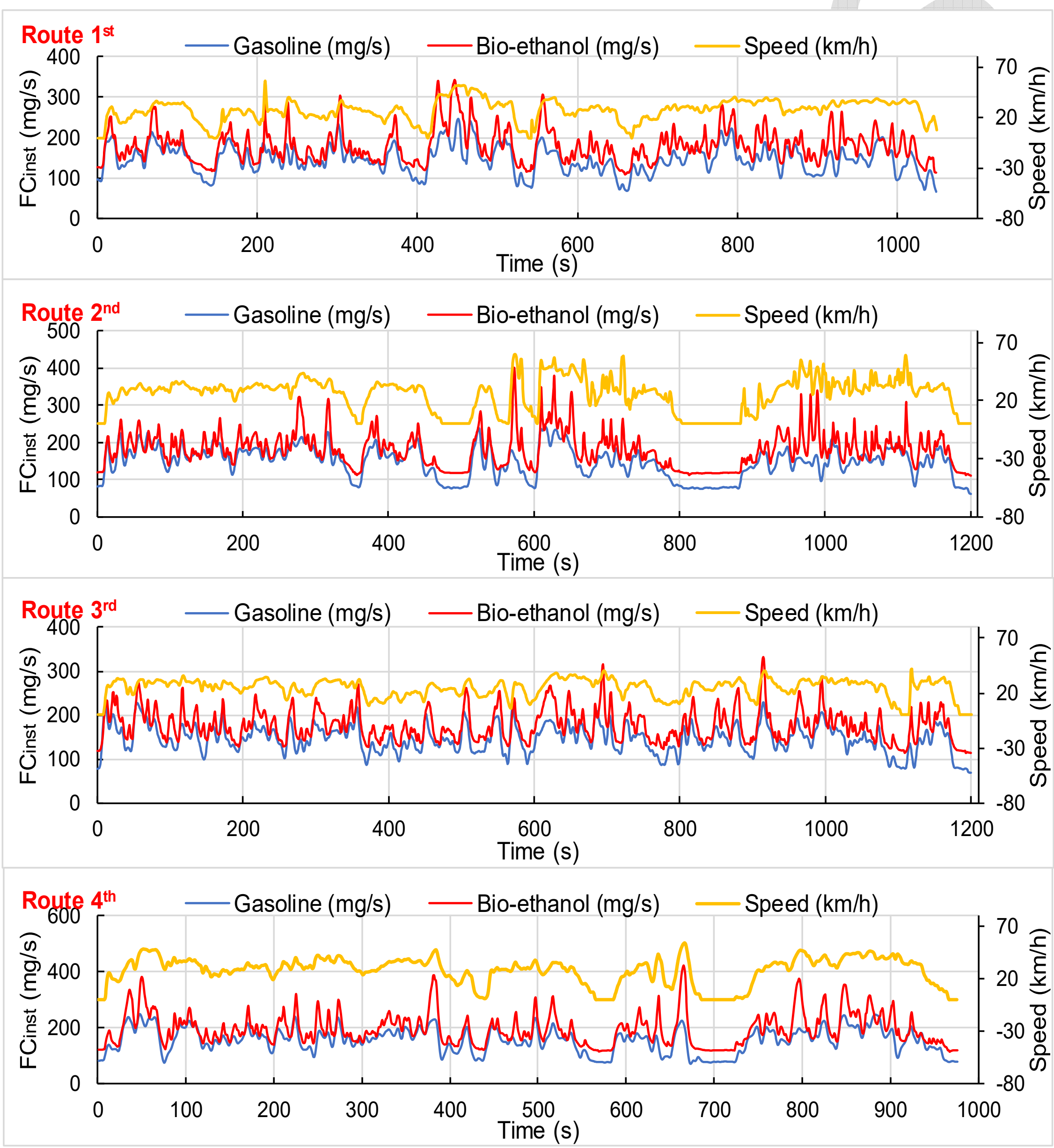

Fig. 8. Simulated FC_{inst} as a function of time-based on on-road driving parameters

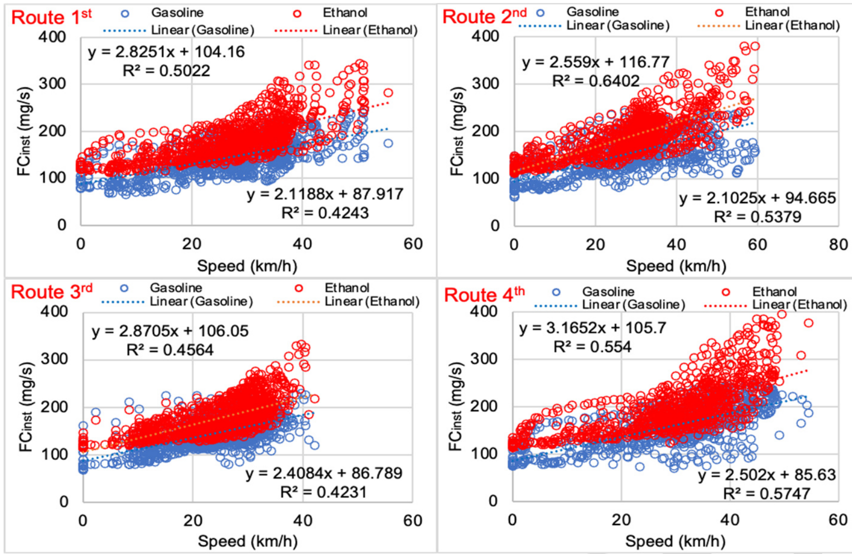

Fig. 9. The correlation between vehicle speed and FC_{inst}

The results in Fig. 9 illustrate the relationship between travel speed and FC_{inst} across four different routes using scatter plots. The results indicate a general trend of increasing FC with higher speeds, as represented by linear regression equations with slopes ranging from 4.9296 to 6.7245. The coefficient of determination R^2 varies between 0.8747 and 0.9414, suggesting that speed significantly influences FC, though other factors may also contribute. Among the four routes, the 3rd route exhibits the highest fuel consumption, with regression coefficients of 6.7245 and 5.5623, while the 2nd route shows the lowest values at 6.0455 and 4.9296. The 4th route demonstrates an intermediate consumption level but with a high model fit, as indicated by a value of 0.917. These findings highlight variations in FC across different routes, which may be attributed to road conditions, traffic density, or driving behavior. This study provides valuable insights for optimizing fuel-efficient driving strategies by identifying optimal speed ranges to minimize fuel consumption.

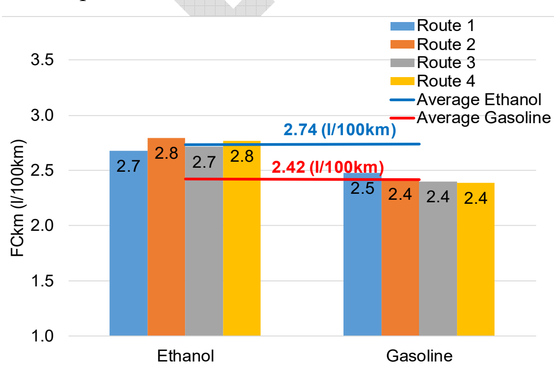

Fig. 10. Comparison of the average fuel consumption

3.3. Comparison of Average Fuel Consumption

As shown in (4), the FC_{km} is calculated based on FC_{inst} and the traveled distance. The simulation results indicate that the FC_{km} when using bio-ethanol increases by 8.08% to 15.9%, with an average increase of 13.12% across four representative routes corresponding to different regions (Fig. 10). This result is consistent with the fact that bio-ethanol has a lower LHV than gasoline and a lower air-fuel (*A/F*) ratio, which necessitates a higher FC to maintain the appropriate mixture ratio.

In addition to the fuel injection pulse width being increased by a certain factor when the engine operates on bio-ethanol to regulate the air-fuel mixture ratio, the ECU (Electronic Control Unit) also makes adjustments based on operating conditions and feedback signals from the lambda sensor in the exhaust system. According to theoretical calculations, the fuel amount needs to increase by a factor of 1.6 (equivalent to an increase of 60%) when switching the engine from gasoline to bio-ethanol [7]. However, the simulation results show that under real driving conditions, the additional bio-ethanol fuel consumption increases by approximately 13.12%.

These results are quite consistent with the experimental findings conducted on carbureted motorcycles in the study by Duc *et al.* [4], where average fuel consumption increased by approximately 30% when bio-ethanol completely replaced gasoline.

It is important to note that the increase in FC alone does not fully reflect the nature of the issue. Since bio-ethanol has a significantly lower LHV than gasoline (by approximately 34%), the total energy input actually decreases. In this context, the parameter of average energy consumption (EC_{km}) will be used to evaluate the engine's efficiency, as defined in the following:

$$EC_{km} = FC_{km} \times \rho_{fuel} \times LHV \quad (5)$$

where: EC_{km} denotes the EC per unit of travelled distance (MJ/km), and *LHV* denotes the lower heating value of fuels.

From the simulation results (Fig. 11), it can be observed that bio-ethanol consumes less energy than gasoline. This is because gasoline has a higher energy density compared to bio-ethanol, which reduces the discrepancy in EC. As a result, the difference in EC is approximately 24.84%. The simulated calculation results are higher than the experimental results on carbureted motorcycles using bio-ethanol as a gasoline substitute, as conducted by Duc *et al*. [4], in which the average brake-specific energy consumption of the test motorcycle at full throttle conditions was reduced by 19% as speed varied.

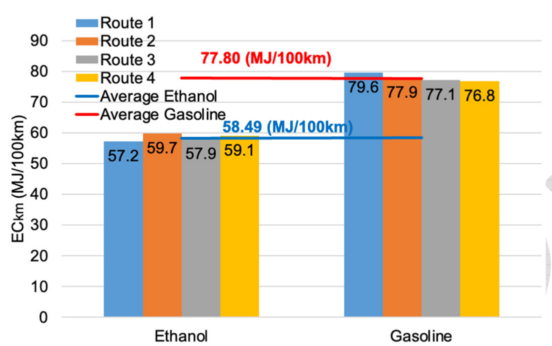

Fig. 11. Comparison of the average energy consumption

4. Conclusion

The paper presents the results of a simulation study evaluating the fuel consumption of an electronic fuel injection motorcycle when using bio-ethanol as a complete substitute for gasoline. The simulation model was developed using AVL-Cruise, achieving a high level of accuracy, with statistical validation metrics of coefficient of determination R^2 was 0.8778, the root mean square error was 28.70 mg/s, the root mean square percentage error was 22.89%, and an average fuel consumption deviation of less than 5% between simulation and experimental results. The distribution of measured instant fuel consumption according to the WMTC cycle closely matches the distribution based on simulated data, with an overlap rate reaching up to 80.23%. The simulation results for gasoline and bio-ethanol indicate that, on average, fuel consumption increases by approximately 13.12% when bio-ethanol replaces gasoline. However, energy consumption decreases by up to 24.84%. This demonstrates the effectiveness of bio-ethanol as a gasoline substitute, as the combustion process is more efficient, leading to lower overall energy consumption. Future research may focus on analyzing emission-related issues of motorcycles when converting from gasoline to bio-ethanol.

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