https://doi.org/10.31436/iiumej.v27i2.4062

Impact of Aggressive and Moderate Driving Intensity on Vehicle Air–Fuel Ratio Stability

MOHAMAD NORSYAFIQ AB HAMID[1], MUHAMMAD YUSRI ISMAIL[1,2*], NAJMI HAZIQ BADRULHISAM[1,2,3,4]

[1]*Faculty of Mechanical and Automotive Engineering Technology, Universiti Malaysia Pahang Al-Sultan Abdullah, Pekan, Malaysia*
[2]*Automotive Engineering Centre, Universiti Malaysia Pahang Al-Sultan Abdullah, Pekan, Malaysia*
[3]*Centre for Sustainable Advanced Engineering Design, Faculty of Engineering, Built Environment, and Information Technology, SEGi University, Selangor, Malaysia*
[4]*Faculty of Engineering, Built Environment, and Information Technology, SEGi University, Selangor, Malaysia*

**Corresponding author: yusriismail@umpsa.edu.my*

(Received: 24 November 2025; Accepted: 24 February 2026; Published online: 10 May 2026)

ABSTRACT: Aggressive driving behavior occurs when drivers neglect traffic rules, leading to violations, accidents, and increased road hazards. Such behavior endangers the driver and places other road users at risk. In contrast, moderate driving reflects disciplined patterns that reduce risks and improve vehicle efficiency. This study examines the influence of aggressive and moderate driving behaviors on engine performance, with a focus on air–fuel ratio (AFR) stability. The investigation used On-Board Diagnostics (OBD-II) data collected during 11.7 km driving sessions under two conditions: aggressive and moderate. The test vehicle, equipped with a 1.8-liter engine, was driven at controlled speeds. Aggressive driving was defined as driving in the 60–90 km/h range, while moderate driving occurred below 60 km/h, representing typical urban operation. Results show distinct differences in AFR behavior. Aggressive driving produced greater instability, with richer AFR outliers near 12.5, higher global wavelet spectrum (GWS) peaks of about 40 units compared to 20, and longer time in fuel-rich regions (12–17% versus 5–14%). These fluctuations indicate unstable combustion, increased fuel use, and higher emissions. In contrast, moderate driving maintained a more stable AFR distribution, with a greater proportion of leaner readings (~36% versus 30%) and closer alignment with stoichiometric values. This stability supports improved combustion efficiency, reduced emissions, and better fuel economy. Overall, the findings show that driving intensity significantly influences AFR stability, with moderate driving promoting cleaner and more efficient engine operation.

ABSTRAK: Tingkah laku pemanduan agresif berlaku apabila pemandu mengabai peraturan lalu lintas, menyebabkan pelanggaran, kemalangan dan peningkatan bahaya di jalan raya. Tingkah laku sedemikian membahayakan pemandu dan membahayakan pengguna jalan raya lain. Sebaliknya, pemanduan sederhana mengurangkan risiko dan meningkatkan kecekapan kenderaan. Kajian ini mengkaji pengaruh tingkah laku pemanduan agresif dan sederhana terhadap prestasi enjin, dengan memberi tumpuan kepada kestabilan nisbah udara-bahan api (AFR). Kajian ini menggunakan data Diagnostik Atas Papan (OBD-II) yang dikumpul semasa sesi pemanduan 11.7 km di bawah dua keadaan: agresif dan sederhana. Kenderaan ujian, dilengkapi enjin 1.8 liter, dipandu pada kelajuan terkawal. Pemanduan agresif ditakrifkan pada julat 60–90 km/j, manakala pemanduan sederhana berlaku di bawah 60 km/j, mewakili pemanduan tipikal dalam bandar. Dapatan kajian menunjukkan perbezaan ketara dalam tingkah laku AFR. Pemanduan agresif menghasilkan ketidakstabilan terbesar, dengan AFR terpisah yang lebih tinggi iaitu hampir 12.5, puncak spektrum gelombang global (GWS), iaitu 40 unit lebih tinggi berbanding 20, dan masa lebih lama di kawasan kaya bahan api (12–17% berbanding 5–14%). Turun naik ini menunjukkan pembakaran yang tidak stabil, peningkatan penggunaan bahan api dan pelepasan karbon lebih tinggi. Sebaliknya, pemanduan sederhana mengekalkan taburan AFR lebih stabil, dengan kadar bacaan lebih rendah (~36% berbanding 30%) dan penjajaran hampir pada nilai stoikiometrik. Kestabilan ini menyokong kecekapan pembakaran yang lebih baik, mengurangkan pelepasan dan penjimatan bahan api yang lebih baik. Secara keseluruhan, dapatan kajian menunjukkan bahawa pemanduan yang baik mempengaruhi kestabilan AFR dengan ketara. Pemanduan sederhana menggalakkan operasi enjin yang lebih bersih dan cekap.

KEYWORDS: *Aggressive driving behavior; Moderate driving behavior; Air–fuel ratio (AFR) stability; On-Board Diagnostics (OBD II); Driving styles.*

1. INTRODUCTION

All modern vehicles, whether powered by an internal combustion engine, hybrid systems, or hydrogen, rely on braking systems [1]. The braking system is essential for slowing the vehicle down and preventing collisions [2]. In vehicles equipped with internal combustion engines, braking events are not only mechanical actions but also induce transient engine conditions, particularly during throttle release and reapplication. During deceleration, changes in throttle position and engine load trigger fuel cut-off or enrichment strategies governed by the engine control unit (ECU), which directly affect the air–fuel ratio (AFR). This is due to the working principle of the internal combustion engine, which depends on the throttle position and fuel injection system strategies [3]. These situations will contribute to transient engine conditions that can destabilize the air-fuel ratio, disrupting combustion efficiency and emissions control. These rapid transitions between fuel cut-off, idle control, and acceleration introduce AFR instability, potentially degrading combustion efficiency and emissions performance. Such transient engine behavior is strongly influenced by driver input, especially during abrupt braking and subsequent acceleration [5]. Consequently, driving style plays a critical role in determining AFR response characteristics and overall engine feedback during real-world driving conditions [4].

Driving behavior can be divided into two types: aggressive and moderate. In the event of aggressive driving, the driver tends to maximize the use of fuel due to the rapid acceleration [5]. This also resulted in frequent hard braking, which leads to danger in driving road safety, as well as higher exhaust emissions, which also resulted in inconsistent throttle input [6]. On the other hand, a moderate driving style is associated with smooth throttle control and steady speeds, moving vehicles, which leads to less gradual braking, thus a safer driving style [7]. During aggressive driving, the air-fuel ratio often exhibits rich spikes and inefficient combustion, whereas moderate driving has a lean air-fuel ratio, resulting in a better fuel-air mixture to maintain stoichiometric conditions. Meanwhile, moderate driving is a better cost-effective driving style that contributes to lower exhaust emissions as well [8]. Under aggressive handling conditions, the engine control unit (ECU) often struggles to maintain a stable air-fuel ratio, leading to ineffective combustion. In contrast, moderate driving consistently maintains a more stable air-fuel ratio, improving fuel efficiency and lowering emissions.

Aggressive and moderate driving are two common types of vehicle handling observed on the road, often depending on the driver's situation and environment. Understanding the effects of these driving behaviors on vehicle performance is essential, particularly for improving road safety under real-time or transient driving conditions [9]. From a combustion standpoint, transient driving events are important because they directly affect the air–fuel ratio (AFR), which governs combustion stability, efficiency, and emission formation. However, most existing studies do not clearly link aggressive and moderate driving behaviors to variations in AFR during real-world on-road driving. As a result, there is still a limited understanding of the influence of different driving styles on AFR behavior beyond steady-state conditions.

Kumar and Shen [10] investigated a discrete-time, model-based estimation and control approach for cycle-to-cycle air–fuel ratio (AFR) regulation in spark-ignition engines under transient operation, explicitly addressing combustion imbalance caused by rapid throttle changes. Experimental validation on a full-scale gasoline engine test bench demonstrated that the estimated AFR closely matched lambda-sensor measurements, with errors generally below 3.1% across engine speeds of 1000, 1500, and 2000 $r \cdot min^{-1}$ and engine loads of 60, 120, and 180 $N \cdot m$, confirming improved mixture preparation, enhanced combustion stability, and reduced cycle-to-cycle combustion variability under varying operating conditions.

Daham et al. [11] tested driver variability using a fully warmed-up Euro 2 spark-ignition Ford Mondeo operated on a repeated 0.6 km urban driving loop with multiple junction events. Although mean vehicle speed varied only slightly, large differences in acceleration, throttle position, and throttle jerk were observed among drivers, indicating fundamentally different transient driving behaviors. These rapid throttle transients were shown to disturb the $\lambda = 1$ air–fuel ratio control system, leading to AFR instability and increased cycle-to-cycle combustion variability during real-world driving, particularly under aggressive throttle inputs.

Rimpas D et al. [12] proposed a vehicle monitoring framework that collects key operational parameters such as vehicle speed, engine load, airflow, and fuel consumption through electronic sensors and retrieves them through the OBD-II diagnostic protocol. Experimental validation was conducted over a 5 km urban route under both light and heavy traffic conditions, demonstrating stable and reliable data acquisition throughout the test. Quantitative analysis revealed that aggressive driving behavior, characterized by frequent acceleration and deceleration events, substantially increased fuel consumption, whereas steady driving conditions yielded more consistent engine load profiles and improved fuel efficiency. Notably, the results indicated that vehicles exhibited lower fuel consumption during steady cruising at higher speeds, contradicting the common assumption of uniformly higher fuel consumption at higher speeds. These findings confirm the capability of OBD-based monitoring systems to quantitatively assess the influence of driving behavior on vehicle performance and fuel efficiency.

Zeb et al. [13] developed an OBD-II-based cyber-physical system (CPS) for identifying road bottlenecks and quantifying their associated inefficiencies in terms of fuel consumption, travel time, and CO_2 emissions. The proposed system integrates vehicular parameters, including vehicle speed, engine RPM, mass airflow (MAF), intake air temperature (IAT), and air–fuel ratio (AFR) , acquired via OBD-II, alongside GPS and temporal data transmitted via Wi-Fi to a cloud analytics platform. The solution was experimentally validated on a fixed urban route over five consecutive days, enabling consistent comparison across traffic conditions. Quantitative analysis revealed that two bottlenecks during morning trips accounted for 38 % of total fuel consumption, 31 % of CO_2 emissions, and 31 % of overall travel time, while three evening bottlenecks contributed to 51 % of fuel consumption, 50 % of CO_2 emissions, and 29 % of trip duration. Instantaneous fuel consumption profiles further demonstrated pronounced spikes during low-speed, stop-and-go conditions, confirming the strong coupling between traffic congestion and fuel inefficiency. The study demonstrated that OBD-II-driven CPS frameworks can effectively localize road bottlenecks, quantify their operational costs, and provide valuable data for traffic model calibration and intelligent transportation system development.

Padmanaban et al. [14] compared aggressive and non-aggressive driving behaviors using an on-road dataset and EPA fuel economy cycles, focusing on acceleration patterns, fuel consumption, and environmental impact. Results showed that aggressive driving involved short, intense accelerations linked to higher fuel use and potential vehicle wear, while non-aggressive driving featured smoother, sustained accelerations, supporting better fuel economy and reduced environmental impact.

Li et al. [15] proposed a representing-behavior-based driving style recognition (RB-DSR) method capable of identifying and tracking dynamic changes in driving behavior. The model integrates a driving-style distinction metric with k-means clustering and a genetic algorithm-based feature selection (GA-FS) to optimize representative-behavior recognition. Road tests confirmed its effectiveness for real-time driving style analysis, though the authors noted the need for larger datasets to improve robustness. Muwaffaq et al. [16] examined the relationship between risky driving behaviors and anger expression among Nigerian drivers using Multilevel Latent Class Analysis (MLCA). The study found that younger male drivers were more prone to aggressive anger expression and recommended improved driver training and stricter traffic law enforcement to enhance road safety.

ŚLUSARCZYK and Jurecki [17] developed a WEco index using a driving simulator to assess eco-driving behavior. Testing 37 drivers, the study identified three performance levels, showing significant differences in fuel use and engine RPM, supporting its use in driver training and fleet management. Zhang et al. [18] proposed an eco-driving evaluation method using speed-specific Vehicle-Specific Power (VSP) distributions from 19,779 drivers. The approach established VSP and fuel-rate baselines, revealing a fuel-consumption difference of over 20% between eco and aggressive driving behaviors.

Adavikottu and Velaga [19] analyzed the impact of Aggressive Driving Behavior (ADB) on collision risk using a driving simulator with 58 drivers across aggression levels. Results showed that aggressive drivers reduced time-to-collision (TTC) and speed-reduction time (SRT) by 82% and 38%, respectively, leading to a much higher crash risk. The study highlights that delayed braking and higher approach speeds among aggressive drivers significantly increase the likelihood of accidents. Adavikottu et al. [20] found that aggressive drivers showed 25% lower speed variability, 18% shorter recovery time, and 107% more tailgating, with a 23.77% higher crash risk during car-following. The study underscores the need for safer car-following models in automated driving systems. Ma and Zhang [21] found that aggressive and moderate drivers exhibited greater anxiety and aggression around automated vehicles than around human-driven ones, while defensive drivers showed no change. The study offers insights into improving safety in mixed-traffic systems. Adavikottu and Velaga [22] analyzed the impact of driving aggression on lane change behavior. Aggressive drivers changed lanes up to 59% faster and showed over five times higher crash risk than non-aggressive drivers, underscoring the need for adaptive driver-assistance systems to enhance safety. Kerwin and Bushman [23] examined public perceptions of aggressive driving using videos depicting close following, illegal passing, and near-collision scenarios viewed from different perspectives. Findings showed that tailgating and illegal passing were rated highly aggressive, particularly from a third-person perspective, whereas high speeds alone did not strongly influence perceptions. The study highlights that perceived aggressiveness depends on viewing perspective and individual traits such as anger and driving attitudes.

https://doi.org/10.31436/iiumej.v27i2.4062

This study aims to investigate the relationship between driving behavior and air–fuel ratio (AFR) stability under two distinct driving styles, namely aggressive and moderate driving, using real-time On-Board Diagnostics (OBD-II) data. The experimental tests were conducted along an 11.7 km driving route with speed variations ranging from below 60 km/h (moderate) to 60–90 km/h (aggressive), representing typical urban driving conditions. The focus on AFR behavior under these conditions was emphasized for several reasons: first, AFR stability plays a critical role in ensuring efficient combustion and fuel economy, particularly in transient driving situations; second, real-time AFR response under dynamic throttle conditions remains underexplored, despite its direct relevance to driver behavior and vehicle control systems. To date, few studies have examined AFR variations in response to driver-induced acceleration and braking behavior, with most prior research emphasizing emission or fuel-consumption patterns rather than combustion balance. Moreover, studies of AFR dynamics often focus on laboratory or chassis-dynamometer settings, lacking real-road driving data that reflect natural driving tendencies. Therefore, this study addresses an existing gap by analyzing AFR fluctuations and throttle response behavior under real-world driving conditions, offering insights into how aggressive and moderate driving styles influence combustion stability. The novelty of this study lies in integrating driving behavior analysis with AFR stability assessment via OBD-II monitoring, providing a cost-effective, data-driven method for understanding driver–engine interaction. By quantifying AFR deviations and identifying patterns of fuel-rich and lean operation zones, the study contributes to a deeper understanding of how driving style affects fuel efficiency and engine stability. Furthermore, these findings offer practical implications for developing eco-driving frameworks, adaptive vehicle control algorithms, and driver behavior recognition systems to enhance energy efficiency in real-world conditions.

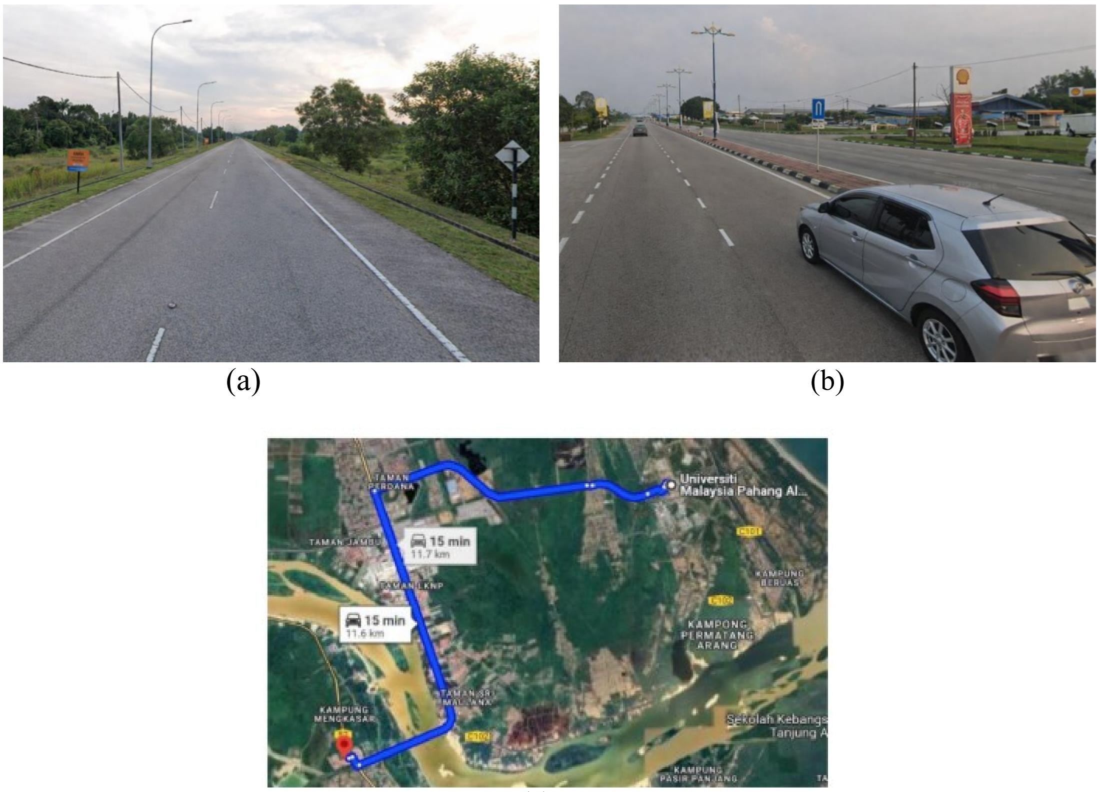
2. METHODOLOGY

A passenger car compliant with OBD-II/EOBD (CAN, ISO-15765; optionally ISO-9141-2/ISO-14230) was used to record vehicle data under driving conditions. The test vehicle used in this study was a passenger car equipped with a 1.8-liter gasoline spark-ignition V6 engine and an automatic transmission. All experiments were conducted under fully warmed-up conditions during urban driving operation. The details of the vehicle are shown in Table 1.

Table 1. Vehicle specification

Parameter	Description
Vehicle category	Passenger car
Model year	2008
Engine configuration	V6, naturally aspirated
Engine displacement	1.8 L
Fuel type	Gasoline
Transmission type	Automatic transmission
Emission standard	Euro 2
Engine operating condition	Fully warmed-up

The vehicle diagnostic data was acquired using a professional OBD-II diagnostic scanner. The data was captured at a sampling rate of 1 Hz. Each driving test was conducted for approximately 15–20 minutes, resulting in a representative dataset for both aggressive and moderate driving styles. For each driving style, three repeated runs were performed to ensure data consistency and repeatability. All experiments were carried out under similar ambient conditions, with temperatures ranging from 28 to 32 °C, dry weather, and normal traffic flow. To minimize driver-related variability, the same driver was used for both aggressive and moderate driving tests, and all runs were conducted on the same route using the same vehicle. All driving experiments were conducted under comparable driving conditions to minimize external influences on vehicle operation. The tests were carried out on the same predefined route and were completed on the same day within a limited time window. Road conditions are mostly urban conditions. Weather conditions were stable, with no rainfall and ambient temperatures remaining within a narrow range. Traffic conditions were moderate and consistent, with no abnormal congestion or incidents observed during the test runs. By maintaining similar roads, weather, and traffic conditions, variations in the recorded data are primarily attributed to differences in driving style rather than environmental factors.



(a) (b)

(c)

Figure 1. Selected test routes consisting of (a) a suburban single-lane road and (b) an urban dual-lane road, both driven in forward and reverse directions, and (c) the Google Maps overview of the complete test route (15–20 min) used for the diagnostic scanner experiment.

During the experiment, the scanner's Vehicle Communication Interface (VCI) was plugged into the OBD-II port to enable real-time data communication (engine speed, air–fuel ratio, coolant temperature, throttle position) via the CAN bus/ISO protocols, facilitating the retrieval of diagnostics from the ECU. The vehicle was driven along a designated 11.7 km route designed to reflect real-world driving conditions, as shown in Figure 1. The journey included a balanced mix of acceleration, steady cruising, deceleration, and idling phases. Throughout the test, the driver operated the vehicle naturally without any imposed controls or restrictions, ensuring that the dataset captured authentic variations in driving behavior. Each AFR reading represents a single snapshot taken during this representative driving session. Each AFR data point corresponds to a snapshot within this driving session. Air–fuel ratio (AFR) measurements were collected at high frequency, resulting in several hundred data points over the 11.7 km driving route. To maintain accuracy, invalid or spurious readings those falling outside the

https://doi.org/10.31436/iiumej.v27i2.4062

sensor's physical limits were excluded from the dataset. For consistency, AFR values greater than 17.5 were capped at 17.5, as readings above this threshold typically correspond to deceleration fuel cut-off (DFCO) events. On the lower end, no AFR values below 12.0 were recorded during this drive. The AFR readings were organized into five fixed intervals for analysis: 12.0–13.1, 13.1–14.2, 14.2–15.3, 15.3–16.4, and 16.4–17.5. The flow chart of the experiment. The flow chart for data recording and analysis is shown in **Figure 3**. The vehicle details are in **Table 1**.

2.1. Criteria for Classification of Aggressive and Moderate Driving Behaviors

The driving conditions are summarized in Table 2. Two driving styles, namely moderate and aggressive, were evaluated under the same route configuration to ensure a fair comparison. For each driving style, the test was repeated three times, with a target duration of 15–20 minutes per run. Moderate driving was conducted at vehicle speeds ranging from 50 to 80 km/h, representing relatively steady driving with minimal braking, typically observed during morning travel after the peak rush hour. In contrast, aggressive driving was characterized by greater speed variations between 80 and 100 km/h, reflecting unsteady driving behavior with frequent acceleration and deceleration due to traffic interactions and slowing-down events. This experimental design allows the assessment of vehicle response and AFR behavior under both steady and transient real-world driving conditions. There is no clear literature that defines aggressive and moderate driving. But these two features are quite common in the investigation of vehicle analysis behavior. A study by Adavikottu and Velaga [19] reported mean vehicle speeds for non-aggressive, moderately aggressive, and aggressive drivers as 40.4 km/h, 49.8 km/h, and 53.7 km/h, respectively. Aggressive drivers maintained speeds that were 13.3 km/h higher than those of non-aggressive drivers and 3.9 km/h higher than those of moderately aggressive drivers, indicating a tendency to sustain higher speeds. Meanwhile, in another study by Kerwin and Bushman [23], tailgating scenarios were evaluated at vehicle speeds of 35 mph (56 km/h) and 65 mph (105 km/h), representing typical urban and highway driving conditions. The degree of aggressiveness was further assessed using Time-to-Collision (TTC), which represents the time required for the following vehicle to collide with the leading vehicle if it were to stop suddenly.

Table 2. Summary of driving styles and test conditions for the urban–suburban mixed driving route

Driving style	**Route type (mixed driving route)**	**Runs (repeat)**	**Target duration per run**	**Variable driving speed (km/h)**	**Time**
Moderate	Urban–suburban	3	15–20 min	50 – 80 (steady driving with minimum braking)	Morning after rush hour, going to work
Aggressive	Urban–suburban	3	15–20 min	80 – 100 (unsteady driving due to slowing down)	

2.2. Wavelet Power Spectrum Analysis

Wavelet transform analysis is widely used to evaluate variations in non-stationary time-series signals, particularly under transient operating conditions. In this study, wavelet analysis is applied to air–fuel ratio (AFR) time-series data to investigate temporal and frequency-dependent fluctuations arising from real-world driving behavior. Through this approach, AFR variability can be decomposed simultaneously in both the time and frequency domains. A wavelet can be expressed as a function that has a zero mean and finite energy. A continuous wavelet transform (CWT) for a wavelet function can be expressed as Equation (1) [24]

https://doi.org/10.31436/iiumej.v27i2.4062

$$CWT(a,b) = \frac{1}{\sqrt{|a|}} \int_{-\infty}^{\infty} x(t)\psi^{*}\left(\frac{t-b}{a}\right), \qquad a,b \in R, a \neq 0. \tag{1}$$

To analyze transient AFR variations, the wavelet power spectrum (WPS) and global wavelet spectrum (GWS) are used. The squared magnitude of the continuous wavelet transform (CWT) represents the energy of the AFR signal at a given scale and time. The WPS is obtained by normalizing the wavelet power by the scale parameter, which allows the AFR energy to be compared with a white-noise background [25]. Accordingly, the AFR data are normalized using Equation (2).

$$WPS_n = \frac{|CWT_n(a)|^2}{\sigma^2} \tag{2}$$

GWS is described as a time average and denoted as, W_s, peak location in GWS is the highest periodicity at a particular given time series. Therefore, the formula is as Equation (3).

$$GWS = W_s = \frac{1}{N}\sum_{n=1}^{N}|CWT(a)|^2 \tag{3}$$

Through the combined use of WPS and GWS, the transient characteristics and dominant frequencies of AFR variation under different driving conditions can be effectively identified. Data programming through the MATLAB interface is shown in Figure 2.

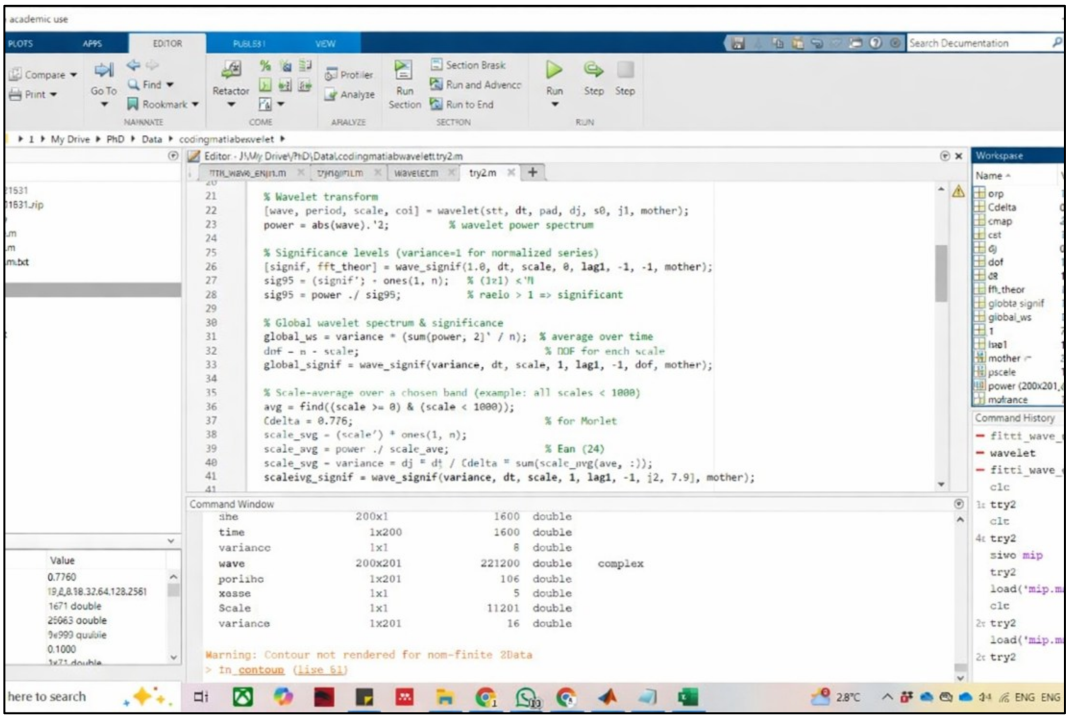


Figure 2. MATLAB interface for data programming.

Implementation of continuous wavelet transform (CWT) for AFR signal analysis, showing the resulting wavelet power spectrum (WPS) and the derived global wavelet spectrum (GWS) used to characterize transient AFR variations in the time–frequency domain.

2.3 Limitations of the Work

The study did not explicitly define controlled acceleration and deceleration profiles, as the primary objective was to capture naturalistic driving behavior. Most of the investigation focused on reflecting real-world driving styles under typical urban and suburban conditions.

Consequently, no emissions data were measured, since the study relied on on-board diagnostics (OBD) data collection rather than controlled engine or emissions testing.

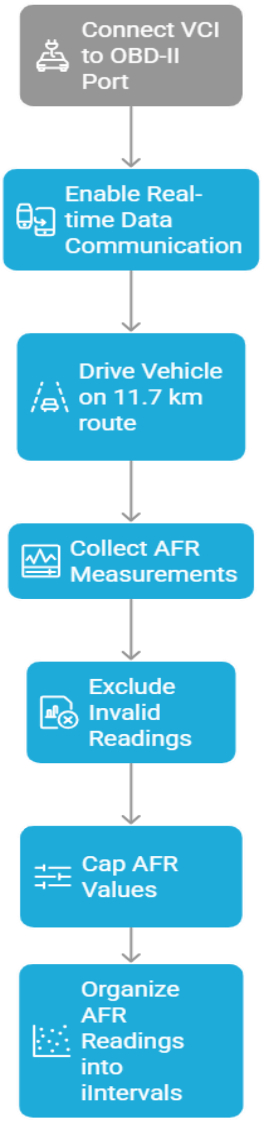


Figure 3. Flowchart for vehicle recording and analysis

3. RESULTS AND DISCUSSION

Figure 4(a) presents the AFR profile for aggressive driving, while Figure 5(b) illustrates the trend for moderate driving. The comparison reveals notable differences in AFR stability between the two conditions. During aggressive driving, the AFR fluctuated widely, ranging between 13.0 and 18.0. The signal shows rapid oscillations with frequent excursions towards lean conditions (above 16.5) and occasional drops to richer values near 13.0. This irregular pattern reflects the influence of sudden throttle inputs and abrupt load variations, which demand continuous fuel delivery corrections by the engine management system. Such fluctuations indicate that the combustion process is less stable under aggressive conditions. In contrast, moderate driving produced a narrower AFR distribution, typically ranging between 14.0 and 17.5. While fluctuations remained, they occurred within a more consistent band, with fewer extreme deviations. This relative stability suggests that smoother acceleration and deceleration kept the AFR closer to the stoichiometric value (≈14.7), thereby facilitating more

https://doi.org/10.31436/iiumej.v27i2.4062

balanced combustion and improving catalytic converter efficiency. The implications of these variations are significant.

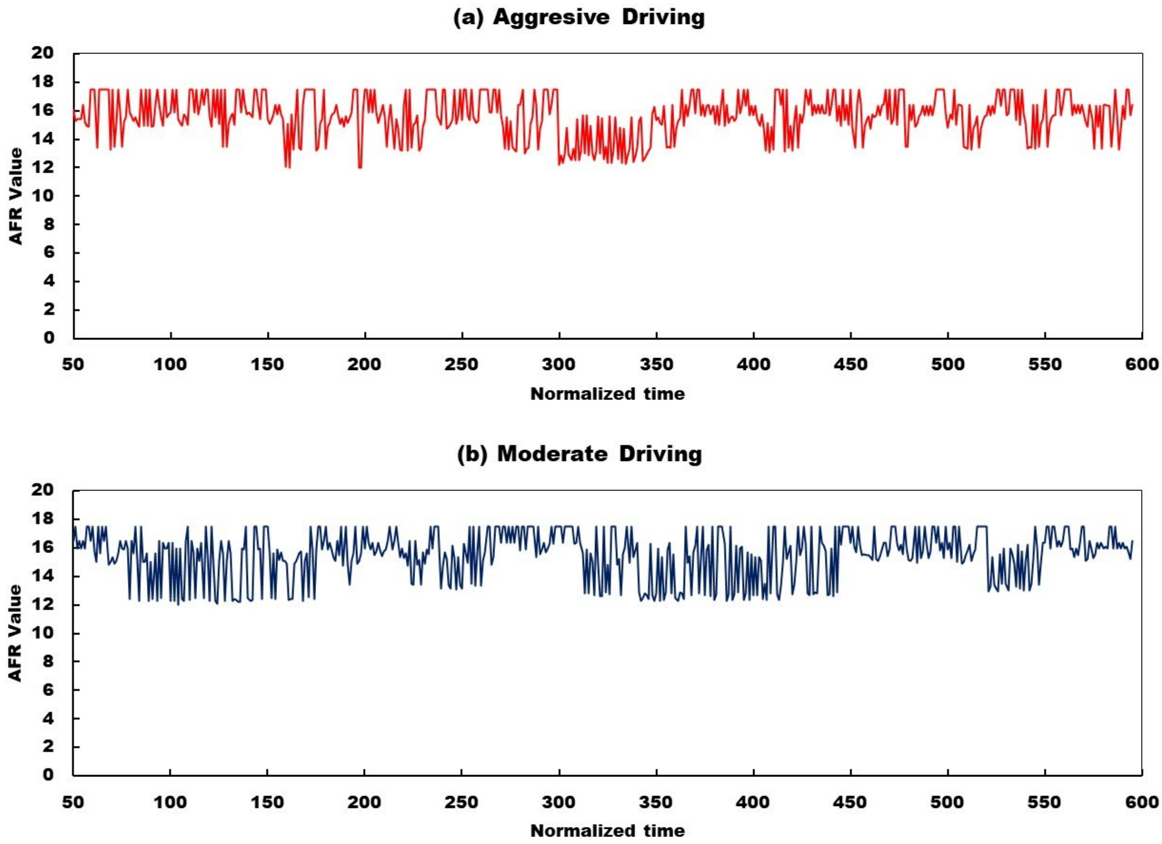
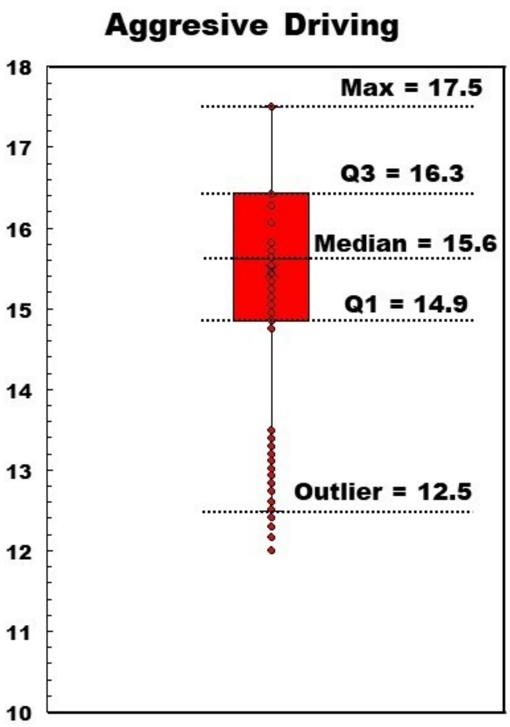


Figure 4. Comparison of AFR dynamics under (a) aggressive and (b) moderate driving conditions

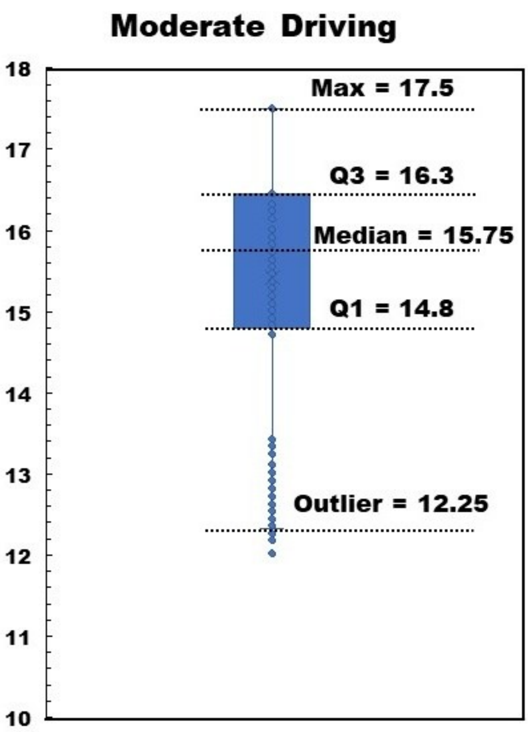
The broader AFR swing observed during aggressive driving may increase transient fuel consumption and adversely affect emissions. Rich excursions (≈13.0–13.5) are associated with incomplete combustion, leading to higher hydrocarbon (HC) and carbon monoxide (CO) emissions. Conversely, lean excursions (≈17.0–18.0) may promote elevated nitrogen oxide (NO_x) formation [26]. On the other hand, the narrower AFR band in moderate driving (≈14.0–17.5) indicates a more controlled combustion process, which supports both fuel economy and emission reduction. Overall, the findings highlight the influence of driving style on AFR dynamics. Aggressive behavior amplifies AFR variability, whereas moderate driving maintains the mixture within a range more favorable for efficient combustion and lower emissions. These results reinforce the importance of adopting smoother driving practices to improve energy efficiency and minimize environmental impact [27].

Figure 5 presents a boxplot analysis of aggressive and moderate driving styles. In this analysis, the mean, median, and outlier values for each driving style can be clearly observed. This is valuable because the boxplot effectively illustrates the characteristics of different driving behaviors and their potential impact on exhaust emissions and fuel consumption. Boxplots provide a concise way to assess whether a driving style reduces emissions, improves fuel efficiency, or increases exhaust output. Unlike conventional graphs, which require multiple figures to show the maximum, minimum, mean, median, and outliers, a single boxplot captures all these statistical features in a single visualization. This makes it a powerful tool for comparing and interpreting the effects of driving behavior on vehicle performance and environmental impact. For aggressive driving, the AFR values ranged from a maximum of 17.5

to a minimum outlier at 12.5. The median was 15.6, with the first quartile (Q1) at 14.9 and the third quartile (Q3) at 16.3. This indicates that 50% of the AFR values were concentrated between 14.9 and 16.3. Despite this relatively narrow interquartile range (IQR = 1.4), the presence of extreme outliers as low as 12.5 highlights the instability in AFR regulation under aggressive throttle changes. Such excursions into richer regions are consistent with transient fuel enrichment during sudden accelerations, which is often employed to avoid knock and maintain power output. In comparison, moderate driving also showed an AFR maximum of 17.5, with outliers observed at 12.25. The median AFR was slightly lower at 15.75, while Q1 and Q3 were 14.8 and 16.3, respectively. This suggests that AFR stability during moderate driving was comparable in terms of spread, but the data distribution was more balanced around the stoichiometric value (≈14.7). Importantly, the lower frequency of extreme outliers indicates that AFR control under moderate driving conditions is less perturbed by sudden fuel-enrichment events. The statistical comparison shows that, while both driving styles operate within similar AFR boundaries (≈12.25–17.5), aggressive driving results in a higher incidence of extreme-rich excursions. These events are associated with incomplete combustion, leading to elevated hydrocarbon (HC) and carbon monoxide (CO) emissions. In contrast, the more balanced AFR distribution observed in moderate driving conditions suggests improved combustion stability, contributing to better fuel economy and reduced pollutant formation. Overall, the boxplot analysis reinforces earlier time-series findings: aggressive driving amplifies AFR variability and increases the likelihood of rich excursions, whereas moderate driving keeps AFR closer to stoichiometric balance, with fewer extreme deviations. This confirms the critical role of driving style in shaping engine combustion behavior and its environmental impact [28].



(a)



(b)

Figure 5. Comparison of key statistical features (max, min, median, quartiles, outliers) for (a) aggressive vs. (b) moderate driving

Figure 6 shows the AFR frequency distribution for aggressive and moderate driving. The results highlight how different driving behaviors influence the proportion of time the engine operates within specific AFR ranges. Under moderate driving, AFR values are more frequently concentrated in the leaner range of 15.3–16.4, with a relative frequency of approximately 36%, compared to 30% for aggressive driving. This indicates that smoother throttle application allows the engine to operate more consistently in a lean-to-stoichiometric region, which is generally favorable for fuel economy. Moderate driving also shows a higher proportion of values in the 12.0–13.1 range (~18%), reflecting occasional rich mixtures, likely linked to acceleration or load demands. Conversely, aggressive driving demonstrates a more even spread across AFR ranges. While still showing a dominant proportion in the 15.3–16.4 and 16.4–17.5 ranges (~30–31%), aggressive driving exhibits a noticeably higher frequency in the 13.1–14.2 and 14.2–15.3 ranges (12–17%) compared to moderate driving (5–14%). This suggests that aggressive throttle actions lead to more frequent transitions into richer operating zones, corresponding to the increased fuel delivery required during sudden load changes. Taken together, these findings suggest that while both driving modes spend significant time in the 15.3–17.5 range, moderate driving favors leaner AFR stability, whereas aggressive driving is associated with greater variability and richer excursions. From a practical perspective, this implies that moderate driving supports fuel-efficient operation, while aggressive driving, with its richer transients, could contribute to higher fuel consumption and elevated hydrocarbon (HC) and carbon monoxide (CO) emissions.

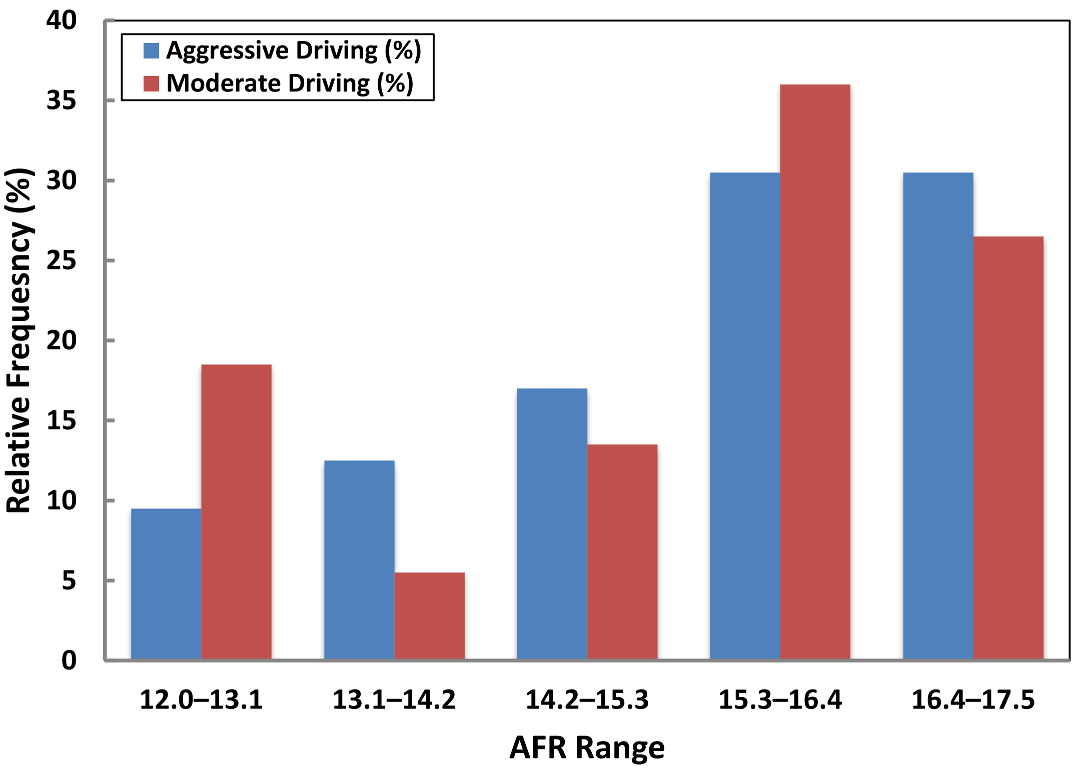
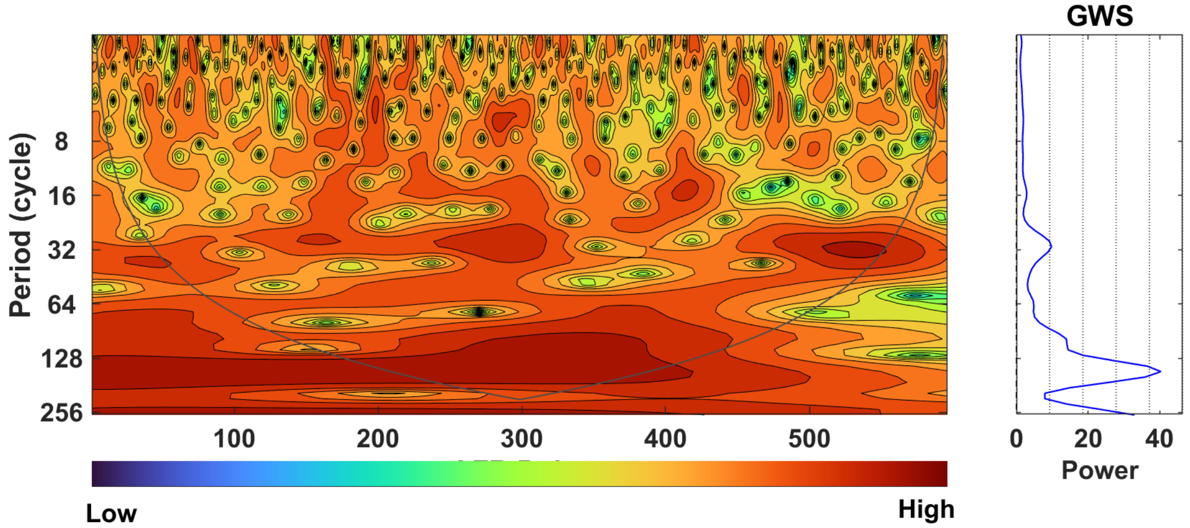


Figure 6. Frequency distribution of Air–Fuel Ratio (AFR) under aggressive and moderate driving

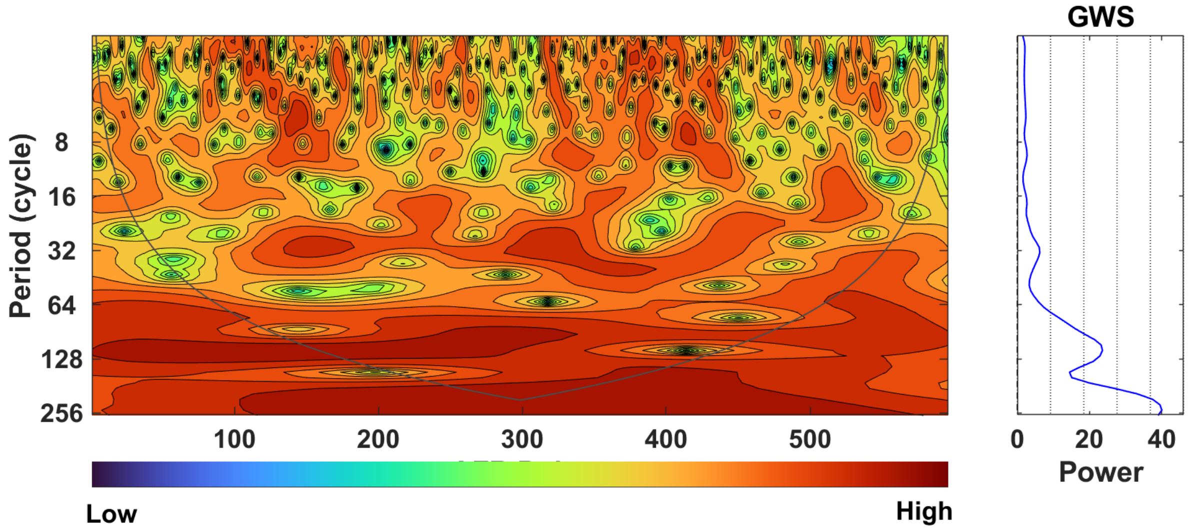
Figure 7(a) illustrates the aggressive driving style, while Figure 7 (b) represents the moderate driving style. These results, derived from the raw dataset, highlight the wavelet power spectrum's (WPS) ability to detect abnormalities in driving behavior. Driving style is widely recognized as a key factor that directly influences fuel efficiency, vehicle performance, and exhaust emissions. By applying both the wavelet power spectrum and the global wavelet spectrum (GWS), it is possible to evaluate how variations in the air–fuel ratio (AFR) reflect

https://doi.org/10.31436/iiumej.v27i2.4062

engine dynamics across different time and frequency domains. The comparative assessment of aggressive and moderate driving reveals a clear distinction in energy distribution, as observed in power levels and cycle ranges. These characteristics are strong indicators of the driver's behavioral condition. For aggressive driving, the wavelet power spectrum reveals a pronounced concentration of high-energy components, quantitatively reflected by dominant global wavelet spectrum peaks reaching approximately 40 power units. These high-energy components are distributed across both low-cycle bands (8–16 cycles) and higher-cycle bands (64–128 cycles), indicating AFR disturbances occurring over multiple time scales due to rapid throttle modulation and braking events.



(a) Aggressive driving style



(b) Moderate driving

Figure 7. Wavelet Power Spectrum (WPS) and Global Wavelet Spectrum (GWS) analysis of (a) aggressive and (b) moderate driving styles

The global wavelet spectrum further confirms these findings, showing sudden peaks reaching up to 40 power units. Multiple dominant peaks are visible across both the lower-cycle region (8–16 cycles) and the higher-cycle region (64–128 cycles), indicating an unstable AFR condition. Such instability in AFR control leads to poor fuel-consumption management, elevated exhaust emissions, and greater mechanical stress on the vehicle's powertrain. In contrast, moderate driving exhibits a lower overall spectral energy density, with global wavelet spectrum power values predominantly between 10 and 20 units and a broad dominant peak centered at approximately 20 units. This pattern corresponds to power values ranging between 10 and 20 units in the global wavelet spectrum (GWS). The energy distribution is concentrated mainly within the 32–128 cycle range, reflecting smoother engine operation, steadier driving conditions, and improved throttle control. The peak for moderate driving is observed at approximately 20 units, where it appears broad and sustained, particularly across the 32–128 cycle range. This indicates more stable combustion dynamics compared to aggressive driving. Isolated smaller peaks are also present within the 128–256 cycle range, but these remain less significant and do not alter the overall stability of the spectrum. Although some peaks remain slightly elevated, the overall trend in moderate driving shows a steadier, more consistent increase in energy compared to aggressive driving. In particular, the dominant global wavelet spectrum under moderate behavior is concentrated at longer cycles, unlike aggressive driving, which displays multiple scattered peaks. From an engineering perspective, this driving style enhances engine durability, improves driving comfort, and supports eco-driving efficiency. The more stable AFR control under moderate driving contributes to better fuel consumption management and lower vehicle emissions [29]. By comparison, aggressive driving produces a GWS peak of up to 40 units, nearly double the value of moderate driving, highlighting its greater instability and inefficiency.

4. CONCLUSIONS

Aggressive and moderate driving behaviors produce clearly distinguishable air–fuel ratio (AFR) patterns, with aggressive driving causing greater AFR instability and moderate driving supporting more consistent AFR regulation. The results show that aggressive driving, characterized by frequent and abrupt throttle inputs, leads to higher AFR variability, repeated rich excursions with AFR values reaching as low as 12.5, and stronger oscillatory behavior, as reflected by global wavelet spectrum peak magnitudes of up to 40 units across multiple cycle ranges. In addition, rich AFR operating regions occur more frequently under aggressive driving, accounting for approximately 12–17% of total driving time, indicating repeated transient fuel enrichment and greater deviation from the stoichiometric condition. In contrast, moderate driving maintains AFR values closer to the stoichiometric ratio of approximately 14.7, demonstrates a higher proportion of smoother lean operation within the 15.3–16.4 AFR range at about 36%, and produces fewer extreme AFR outliers in the boxplot analysis, confirming lower AFR dispersion and more stable combustion control. Overall, the findings demonstrate that driving behavior has a direct, measurable effect on AFR stability, distribution, and transient enrichment patterns, with aggressive driving contributing to less stable AFR regulation and moderate driving promoting smoother, more efficient engine operation. Future work should extend this analysis to different vehicle types, engine technologies, road gradients, and traffic conditions to establish a more generalizable relationship between driving behavior and AFR dynamics.

ACKNOWLEDGEMENT

The authors would like to thank Universiti Malaysia Pahang Al-Sultan Abdullah (UMPSA) for providing financial support under the research grant scheme No. PGRS230386 and laboratory facilities.

https://doi.org/10.31436/iiumej.v27i2.4062

REFERENCES

[1] A. Boretti, "Advancing sustainable mobility: Integrating flywheel kinetic energy recovery systems with high-efficiency hydrogen internal combustion engines," *Int. J. Hydrogen Energy*, vol. 125, pp. 354–363, 2025.

[2] N. Venkatachalam, A. P. V. Manoharan, K. Ravichandran, P. V. Aravinth, and T. H. Sardar, "Speed Breaker and Vehicle Accident Detection with Alert Sensors," in *Applications of Computational Learning and IoT in Smart Road Transportation System*, Springer, 2025, pp. 17–36.

[3] C. A. MacCarley, "Engines and Fuels," in *Non-Petroleum Automotive Transportation*, Springer, 2025, pp. 61–96.

[4] Y. Ling, Z. Ma, Y. Song, Q. Zhang, X. Weng, and X. Ma, "Bus driver deceleration behavior modeling at intersections using multi-source on-board sensor data," *J. Public Trans.*, vol. 27, p. 100123, 2025.

[5] F. Haque and M. A. Abas, "Review of Driving Behavior Towards Fuel Consumption and Road Safety," *Jurnal Mekanikal*, 2018.

[6] E. G. Giakoumis, *Driving and engine cycles*, vol. 1. Springer, 2017.

[7] T. Wei, T. Zhu, and M. Zhang, "Impact of driving style on rear-end crash risk in leading vehicle emergency braking situations," *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, p. 09544070251323635, 2025.

[8] A. Moawad, M. Zebiak, J. Han, D. Karbowski, Y. Zhang, and A. Rousseau, "Effect of adaptive cruise control on fuel consumption in real-world driving conditions," *Nat. Commun.*, vol. 15, no. 1, p. 10016, 2024.

[9] M. S. H. Nahid, T. Z. Tila, and T. S. Seecharan, "Detecting emotional arousal and aggressive driving using neural networks: A pilot study involving young drivers in Duluth," *Sensors*, vol. 24, no. 22, p. 7109, 2024.

[10] M. Kumar and T. Shen, "Estimation and feedback control of air-fuel ratio for gasoline engines," *Control Theory and Technology*, vol. 13, no. 2, pp. 151–159, 2015.

[11] B. Daham, H. Li, G. E. Andrews, J. Tate, K. Ropkins, and M. Bell, "Driver Variability Influences on Real World Emissions at a Road Junction using a PEMS," SAE Technical Paper, 2010.

[12] D. Rimpas, A. Papadakis, and M. Samarakou, "OBD-II sensor diagnostics for monitoring vehicle operation and consumption," *Energy Reports*, vol. 6, pp. 55–63, Feb. 2020, doi: 10.1016/j.egyr.2019.10.018.

[13] A. Zeb *et al.*, "ON-BOARD DIAGNOSTIC (OBD-II) BASED CYBER PHYSICAL SYSTEM FOR ROAD BOTTLENECKS DETECTION," 2022.

[14] G. Padmanaban, F. Feng, E. Dai, A. Saini, G. Hu, and Y. Zhao, "A Comparative Analysis of Acceleration and Deceleration Profiles for Aggressive Driving Styles and Fuel Economy Test Cycles," SAE Technical Paper, 2025.

[15] B. Li *et al.*, "Representing-behavior-based online driving style recognition and its road verification," *Eng. Appl. Artif. Intell.*, vol. 156, p. 111241, 2025.

[16] M. S. Labbo, X. Jiang, S. A. Wada, G. J. de Dieu, and N. D. Bala, "Road rage patterns in Nigeria: A multi-level latent class analysis," *Case Stud. Transp. Policy*, p. 101471, 2025.

[17] K. ŚLUSARCZYK and R. Jurecki, "The use of a vehicle simulator for eco-driving research," *Combustion Engines*, 2025.

[18] L. Zhang, Z. Zhu, Z. Zhang, G. Song, Z. Zhai, and L. Yu, "An improved method for evaluating eco-driving behavior based-on speed-specific vehicle-specific power distributions," *Transp. Res. D Transp. Environ.*, vol. 113, p. 103476, 2022.

[19] A. Adavikottu and N. R. Velaga, “Analysis of speed reductions and crash risk of aggressive drivers during emergent pre-crash scenarios at unsignalized intersections,” *Accid. Anal. Prev.*, vol. 187, p. 107088, 2023.

[20] A. Adavikottu, N. R. Velaga, and S. Mishra, “Modelling the effect of aggressive driver behavior on longitudinal performance measures during car-following,” *Transp. Res. Part F Traffic Psychol. Behav.*, vol. 92, pp. 176–200, 2023.

[21] Z. Ma and Y. Zhang, “Driver-automated vehicle interaction in mixed traffic: Types of interaction and drivers’ driving styles,” *Hum. Factors*, vol. 66, no. 2, pp. 544–561, 2024.

[22] A. Adavikottu and N. R. Velaga, “Modeling the impact of driving aggression on lane change performance measures: steering compensatory behavior, lane change execution duration and crash probability,” *Transp. Res. Part F Traffic Psychol. Behav.*, vol. 103, pp. 526–553, 2024.

[23] T. Kerwin and B. J. Bushman, “Measuring the perception of aggression in driving behavior,” *Accid. Anal. Prev.*, vol. 145, p. 105709, 2020.

[24] M. R. Saxena and R. K. Maurya, “Characterization of cycle-to-cycle variations in conventional diesel engine using wavelets,” in *Advances in internal combustion engine research*, Springer, 2017, pp. 135–155.

[25] C. Torrence and G. P. Compo, “A practical guide to wavelet analysis,” *Bull. Am. Meteorol. Soc.*, vol. 79, no. 1, pp. 61–78, 1998.

[26] Mashruk *et al.*, “Perspectives on NO X Emissions and Impacts from Ammonia Combustion Processes,” *Energy & Fuels*, vol. 38, no. 20, pp. 19253–19292, 2024.

[27] M. Batallas and P. Molina, “Developing a Methodology to Reduce Fuel Consumption and Classify Driving Styles for a Fleet of Vehicles,” in *International Conference on Science, Technology and Innovation for Society*, Springer, 2024, pp. 185–194.

[28] H. Abediasl, A. Ansari, V. Hosseini, C. R. Koch, and M. Shahbakhti, “Real-time vehicular fuel consumption estimation using machine learning and on-board diagnostics data,” *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, vol. 238, no. 12, pp. 3779–3793, 2024.

[29] S. Yoo, J. Shin, and S.-H. Choi, “Machine learning vehicle fuel efficiency prediction,” *Sci. Rep.*, vol. 15, no. 1, pp. 1–20, 2025.