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IMPACT OF DRIVING CYCLES ON BLACK CARBON EMISSIONS FROM DIESEL ENGINES: A CASE STUDY FOR BUS IN VIETNAM

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Abstract. Black carbon (BC) from diesel buses is a major contributor to urban $PM_{2.5}$ and a significant short-lived climate forcer. This study quantifies how operation-mode distributions (Bins) and vehicle-specific power (VSP) characteristics across seven bus driving cycles influence the bus's BC emissions. MOVES software was used to simulate bus BC emissions following selected driving cycles. A representative EURO II diesel bus (60-89 seats; 10 years in service) was used as the case study, while fuel and meteorology were held constant to isolate the effect of driving patterns. The driving kinematic attributes, VSP probability density, and Bin frequencies were analyzed across cycles. The New York City cycle recorded the highest $PM_{2.5}$ and BC emissions (0.859 and 0.599 g/km, respectively), reflecting a driving pattern characterized by a large share of idling time, dominance of Bins 12-13, and the occurrence of high-VSP phases. The Transit Coach Operating Duty Cycle had the lowest $PM_{2.5}$ and BC emissions (0.256 g/km and 0.196 g/km, respectively), indicating a shift toward Bin 22 and an almost complete absence of very high-VSP bins. The Hanoi bus driving cycle produced intermediate values (0.427 g $PM_{2.5}$/km; 0.324 g BC/km), in line with Bins 12-14, which are typical of the city's stop-and-go traffic. Across cycles, BC contributed about 70-78% of $PM_{2.5}$ emissions. The results suggest practical ways to reduce BC and $PM_{2.5}$ in the short term, particularly when technological advancements are limited, such as reducing idling and aggressive acceleration, and improving steady-speed operation.

Keywords: driving cycle, black carbon, diesel bus, MOVES.

1. INTRODUCTION

Transportation is a key driver of economic and social development, forming an integral part of contemporary economies. Nevertheless, its heavy reliance on fossil fuels, accounting for nearly 91% of final energy consumption [1], poses significant challenges for humanity today. In 2022, global greenhouse gas (GHG) emissions from the transport sector reached nearly 8 Gt CO_2, marking a 3% increase compared to 2021 [1]. In Vietnam, GHG emissions from the transport sector accounted for 18% of the total energy-related emissions in 2014 and are projected to remain on an upward trajectory [2]. Therefore, it is necessary to strictly control pollutant emissions from the transport sector, especially in light of Vietnam's commitment to achieving the net-zero emissions target by 2050.

In the context of rapid urbanization and increasing travel demand, buses remain a crucial component of public transportation systems in many developing countries, including Vietnam. The fact is that the bus was considered one of the key measures to reduce air pollutant emissions in Vietnam, as outlined in Vietnam's Nationally Determined Contribution (NDC) 2022. However, these vehicles are significant sources of pollutants that not only affect air quality but also have adverse impacts on public health and climate change. One of the key pollutants is Black Carbon (BC), recognized as a strong climate-warming agent and associated with respiratory and cardiovascular diseases [3, 4]. BC is a key constituent of fine particulate matter ($PM_{2.5}$), primarily formed through the incomplete combustion of fossil fuels and biomass [4].

BC emissions from diesel buses are influenced not only by engine and fuel characteristics but also by driving cycles, which represent the real-world operating conditions, such as speed, acceleration, and stop-and-go patterns. Existing studies in Vietnam have primarily focused on evaluating exposure risks and examining the effectiveness of mitigation strategies. For instance, Quang và cộng sự [5] revealed that inhalated BC concentrations for motorcycle riders ($\approx$ 29 μg/m^3) were more than three times higher than inside buses ($\approx$10 μg/m^3). In terms of mitigation strategies, Hanoi bus rapid transit systems have demonstrated co-benefits in reducing particulate emissions, including BC, by 17-22% compared to conventional buses [6]. This means that existing studies in Vietnam have mainly examined exposure levels or the co-benefits of mitigation measures, but the relationship between driving cycles and BC emissions has not been quantified. This gap is particularly important because driving patterns, including speed fluctuations, acceleration events, and idling, directly affect combustion efficiency and transient engine loads, which are key determinants of BC formation. In contexts where rapid technology upgrades are challenging, understanding this relationship can provide practical, low-cost opportunities for emission reduction.

Therefore, this study aims to quantify the influence of driving cycle characteristics on BC emissions from diesel buses under real-world operating conditions. To achieve this, vehicle emissions are typically assessed using two primary approaches: experimental measurement and model-based simulation. In which the vehicle emission measurement technique requires substantial costs, particularly when applied to heavy-duty vehicles. Currently, in Vietnam, heavy-duty vehicle engine emission testing laboratories can only measure emissions on engine dynamometers, following engine-based test cycles rather than actual vehicle driving cycles. In contrast, emission simulation offers the advantage of saving time and reducing costs, particularly when estimating vehicle emissions under different driving cycle scenarios. Furthermore, the accuracy of simulation software has been steadily improving thanks to advancements in science and technology. As a result, by integrating vehicle-specific power

(VSP) and Bin distributions into the MOVES simulation framework, the study provides an analytical basis for evaluating the impact of different driving patterns and identifying operational strategies that may effectively reduce BC emissions in urban bus systems.

2. METHODOLOGY

The overall methodology for exploring the impact of driving cycles on BC emissions from diesel buses is presented in Fig. 1.

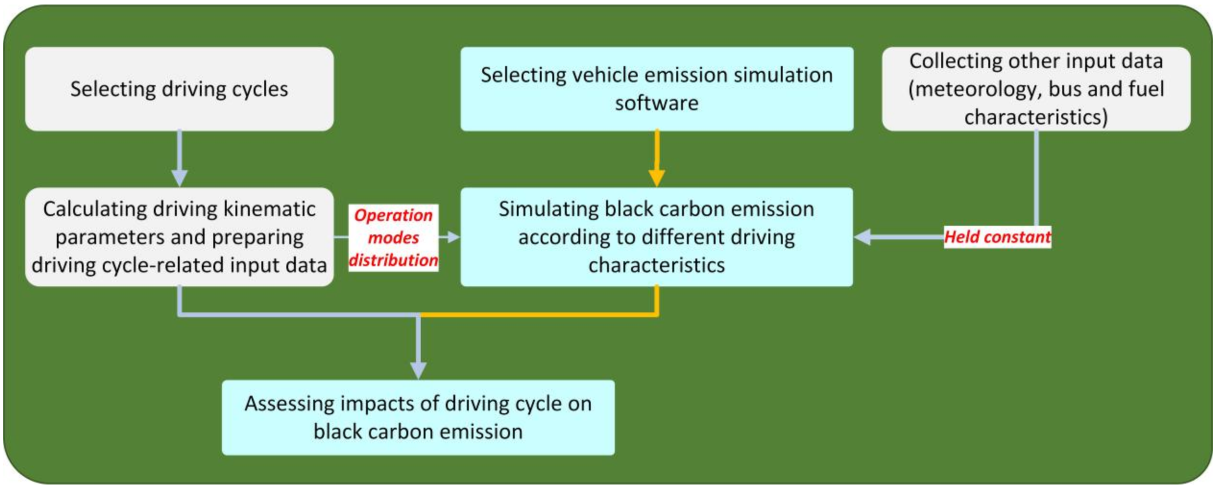

Figure 1. The procedure for assessing the impact of the driving cycle on the diesel bus's BC emissions.

2.1. Selecting vehicle emission simulation software

Examining software for simulating vehicle emissions revealed that these programs fall into two categories: continuous-emission and average-emission simulation. Fig. 2 summarizes several widely used emission simulation software tools in the transport sector.

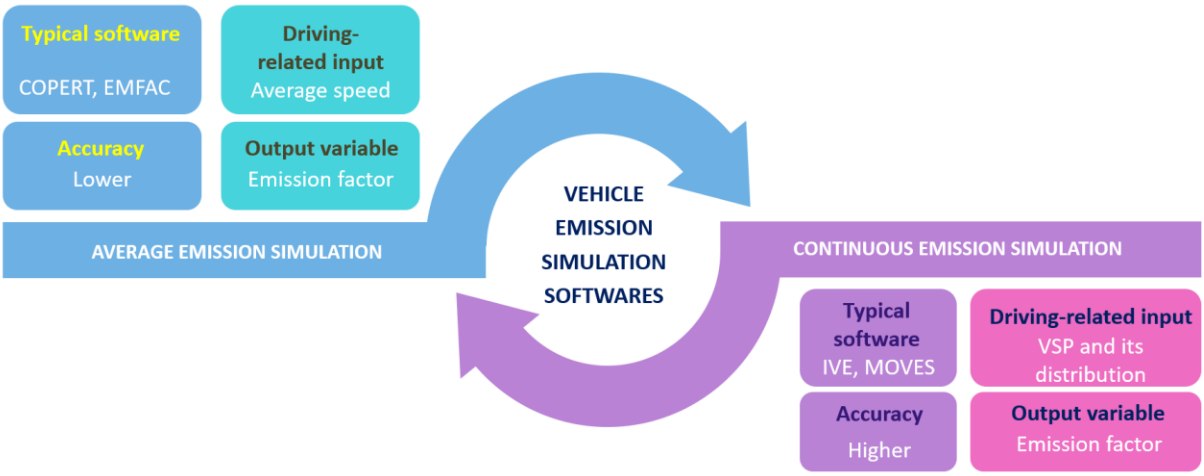

Figure 2. Widely used emission simulation tools in the transport sector.

According to Fig 2, continuous emission simulation models more accurately reflect vehicle emission characteristics than models based solely on average speed. However, their greatest limitation lies in the requirement for detailed input data, particularly regarding driving behavior.

Nevertheless, this limitation makes the approach suitable for analyzing the impact of driving characteristics on vehicle BC emissions. Therefore, the continuous emission simulation model was used in this study. Motor Vehicle Emission Simulator (MOVES) [7] and International Vehicle Emissions (IVE) [8] are two widely used continuous emission simulation tools. IVE is developed by ISSRC with support from EPA, and MOVES is developed by EPA. In which IVE is suitable for emission inventories in developing countries with high accuracy (correlation coefficient > 0.8 [9]); however, it is limited in its ability to detail fuel characteristics, expand to clean fuel types, and has not been updated since 2008. In contrast, MOVES is continuously updated and stands out for its ability to simulate vehicle energy demand and emissions, including those of electric vehicles. Lin et al. confirmed the reliability of MOVES, reporting deviations of only 6.2% for CO_2 and 9.1% for NO_x compared to measured results [10]. Notably, BC emissions can be determined using MOVES, but are not available in IVE.

Although BC is not directly defined in MOVES, it is represented by the Elemental Carbon (EC) component within the $PM_{2.5}$ category. Therefore, to quantify BC emissions, users can use the EC values provided by MOVES. This approach is consistent with the United States Environmental Protection Agency (US. EPA) guidance, which considers EC as a proxy for BC because most EC consists of BC formed during incomplete combustion [11]. Therefore, MOVES was employed in this study. Fig. 3 illustrates the main interfaces of the MOVES software.

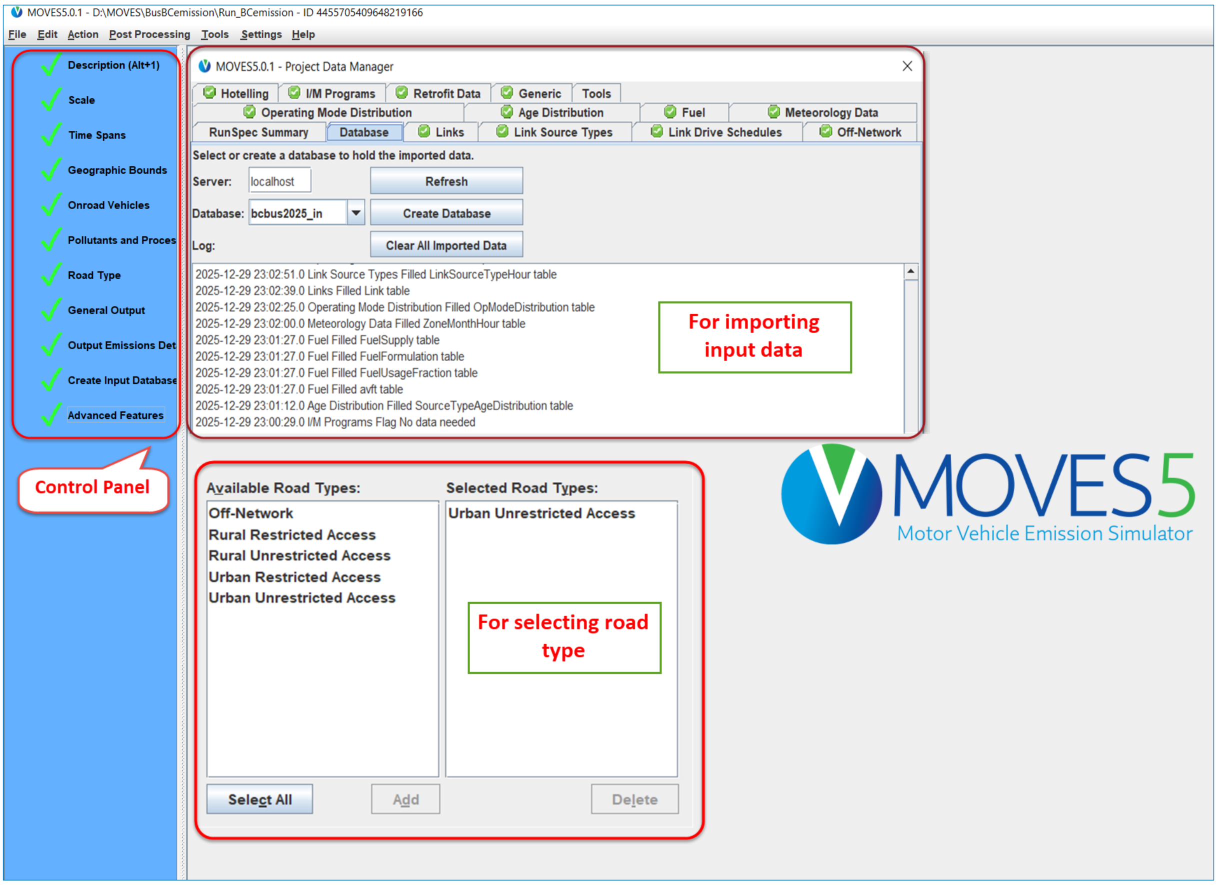

Figure 3. MOVES's main interfaces [7].

2.2. Selecting driving cycles

Under conditions where vehicle type and fuel characteristics are held constant, the driving cycle becomes a fundamental factor influencing emissions. Driving cycles capture the real-world speed and acceleration patterns of vehicles, which strongly affect combustion efficiency and black carbon formation. Therefore, incorporating multiple driving cycles is essential for capturing the variability of real-world operating conditions and demonstrating their influence on BC emissions. Seven bus driving cycles were selected to analyze the impact of driving cycles on the bus's BC emissions in this study, as presented in Table 1. Among them, a driving cycle was developed based on Hanoi's bus driving data by Nguyen and Nghiem [12].

Table 1. Summaries of selected bus driving cycles.

Driving cycle	Abbreviate	Introduction	Source
European Transient Cycle	ETC	Consisting of three parts, in which Part 1, representing city driving characteristics with frequent acceleration, deceleration, and idling, will be used in this study.	[12]
Braunschweig City Driving Cycle	BCC	Simulating typical urban bus driving with numerous stop-and-go events.	[13]
Transit Coach Operating Duty Cycle	TCOC	Initially developed to evaluate heavy-duty vehicle fuel efficiency.	[13]
Manhattan Bus Cycle	MBC	Developed from real-world driving patterns of urban transit buses in Manhattan, New York City.	[12, 13]
New York Bus Cycle	NYC	Developed to represent for actual driving patterns of transit buses in New York City	[12, 13]
Transit Bus Maximum Energy	TBME	Developed from Fleet DNA Project data, which supports advanced vehicle technology development and deployment to reduce costs and emissions.	[13]
Hanoi bus driving cycle	HBDC	Developed to represent urban heavy-duty bus driving characteristics in Hanoi.	[14]

In this study, only Part 1 of the ETC was used, as it represents typical urban driving conditions with frequent stops, accelerations, and decelerations [12]. All time-speed data points of driving cycles above were sourced from DriveCAT (Drive Cycle Analysis Tool) [13], except for HBDC. The HBDC used in this study has a total duration of 3936 seconds, a driving distance of 18.32 km, and a maximum speed of 44 km/h, with an average trip speed of 16.76 km/h. These characteristics represent the typical stop-and-go operating conditions of urban buses in Hanoi.

2.3. Calculating driving kinematic parameters

The driving attribute is quantified by driving kinematic parameters [15]. These parameters are defined for a speed-time series consisting of n data points, with a time step of 1 second and speeds in kph, based on the study by Barlow et al. [15]. This study provides only parameters that have been shown to significantly impact vehicle fuel consumption and emissions. As presented in Table 2.

Table 2. Definitions of key driving kinematic parameters.

Parameters	Notation	Definitions [15]	Used in reference	Equation number
Cruising time ratio (%)	P_c	$P_c = \frac{T_c}{T_{total}} \times 100\%$	[16, 17]	(1)
Creeping time ratio (%)	P_{cr}	$P_{cr} = \frac{T_{cr}}{T_{total}} \times 100\%$	[16, 17]	(2)
Acceleration time ratio (%)	P_a	$P_a = \frac{T_a}{T_{total}} \times 100\%$	[16-18]	(3)
Deceleration time ratio (%)	P_d	$P_d = \frac{T_d}{T_{total}} \times 100\%$	[16-18]	(4)
Idling time ratio (%)	P_i	$P_i = \frac{T_i}{T_{total}} \times 100\%$	[16, 18]	(5)
Average trip speed (km/h)	V_{av}	$V_{av} = 3.6 \times \frac{Dist}{T_{total}}$	[16, 18-20]	(6)
Average positive acceleration (m/s²)	A_{pav}	$A_{pav} = \frac{1}{N_{pos}} \sum_{1}^{n} \begin{Bmatrix} a_i (if\, a_i > 0) \\ 0 (else) \end{Bmatrix}$	[17]	(7)
Average negative acceleration (m/s²)	A_{nav}	$A_{nav} = \frac{1}{N_{neg}} \sum_{1}^{n} \begin{Bmatrix} a_i (if\, a_i < 0) \\ 0 (else) \end{Bmatrix}$	[17]	(8)
Stops per kilometer (stop/km)	N_{rate}	$N_{rate} = 1000 \frac{N_{stop}}{Dist}$	[16]	(9)
Positive kinetic energy (m/s²)	PKE	$PKE = \frac{1}{Dist} \times \sum_{i=2}^{n} \begin{Bmatrix} v_i^2 - v_{i-1}^2 (if\, v_i > v_{i-1}) \\ 0 (else) \end{Bmatrix}$	[16]	(10)
Vehicle-specific power (W/kg)	VSP	$VSP_i = v_i . \{a_i (1 + \varepsilon) + g . g_r + g . C_R\} + 0{,}5 . \rho_a . C_D . \frac{A_F}{m} . v_i^3$	[16, 20-22]	(11)

For buses, MOVES uses the following formula to calculate VSP [23]:

$$VSP_i = v_i . (0.0661 + a_i + g . g_r) + 0.000217 . v_i^3 \quad (12)$$

Where: v_i is the instant speed (m/s); a_i is the instant acceleration (m/s^2); Dist is driving cycle length (km); T_{total} is total time (s); T_c is total cruising time (s); T_{cr} is total creeping time (s); T_a is total acceleration time (s); T_d is total deceleration time (s); T_i is total idling time (s); N_{pos} is total data point with positive acceleration; N_{neg} is total data point with negative acceleration; N_{stop} is the total stopping time; VSP_i is instant specific power (W/kg); ε is a coefficient (ε ≈ 0.1); g is the gravitational acceleration (m/s^2); g_r is the road grade; A_F is vehicle frontal aerodynamic area (m^2); C_R is the rolling resistance coefficient; C_D is the air drag coefficient; ρ_a is air density (kg/m^3).

2.4. Preparing driving feature-related input data

In MOVES, driving characteristics are incorporated into the simulation process according to the frequency of operation modes, as defined by Bin. The definitions of Bins were provided in Table 3 according to [23].

Table 3. Definition of operating modes according to Bin in MOVES.

Bin code	Definition	Bin code	Definition	Bin code	Definition
1	Idling	**22**	0≤VSP<3; 25≤V<50	**30**	30≤VSP; 25≤V<50
11	VSP<0; 1≤V<25	**23**	3≤VSP<6; 25≤V<50	**33**	VSP<6; 50≤V
12	0≤VSP<3; 1≤V<25	**24**	6≤VSP<9; 25≤V<50	**35**	6≤VSP<12; 50≤V
13	3≤VSP<6; 1≤V<25	**25**	9≤VSP<12; 25≤V<50	**36**	12≤VSP; 50≤V
14	6≤VSP<9; 1≤V<25	**26**	12≤VSP; 25≤V<50	**37**	12≤VSP<18; 50≤V
15	9≤VSP<12; 1≤V<25	**27**	12≤VSP<18; 25≤V<50	**38**	18≤VSP<24; 50≤V
16	12≤VSP; 1≤V<25	**28**	18≤VSP<24; 25≤V<50	**39**	24≤VSP<30; 50≤V
21	VSP<0; 25≤V<50	**29**	24≤VSP<30; 25≤V<50	**40**	30≤VSP; 50≤V

In MOVES, the frequency of each operating mode (Bin) serves as a weighting factor that determines the contribution of its corresponding emission rate to the total emissions. For each Bin, MOVES assigns an emission rate based on the operating-mode-based emission tables in its database. The total emissions for a driving cycle are calculated as the weighted sum of these emission rates, where the weights are the fractions of time the vehicle operates in each Bin.

2.5. Collecting other data

Additional data consists of bus fleet features, fuel properties, and meteorological information. Diesel quality-related parameters were collected from Petrolimex, while meteorological information was sourced from the official website https://www.nso.gov.vn/, provided by the National Statistics Office. A representative diesel bus model, with a seating capacity of 60-89 passengers, compliant with EURO II standards, and in service for 10 years [24], was used as the case study in this research. This vehicle type was selected because EURO II diesel buses still constitute a substantial proportion of the current public bus fleet in Hanoi and other major cities. With similar age, engine technology, and operational characteristics, EURO II buses are representative of the diesel buses that continue to dominate real-world operations and contribute significantly to BC emissions.

Because this study aims to estimate the impact of driving cycle on bus BC emissions, these data are held constant throughout the simulation, which involves various driving cycles.

3. RESULTS AND DISCUSSION

3.1. Driving characteristics of driving cycles and differences

To evaluate the influence of driving cycles on BC emissions, it is essential to first examine the kinematic characteristics that define each cycle. These characteristics, such as speed distribution, acceleration patterns, and idling frequency, reflect real-world operating conditions and directly affect combustion efficiency and BC formation. In this section, the selected bus driving cycles are analyzed with respect to 10 key parameters, as shown in Table 4. Comparing these indicators provides insights into the variability among cycles and establishes the foundation for understanding their impact on BC emissions in subsequent analyses.

Table 4. Key kinematic parameters of bus driving cycles.

Parameters	**Driving cycles**							**Difference percentage (%)**	
	BCC	ETC(*)	HBDC	MBC	NYC	TBME	TCOC	Min	Max
Pi (%)	23.7	0.0	7.6	34.1	65.4	35.1	10.7	2.81	198.98
Pa (%)	34.6	37.2	34.2	31	10.8	28.3	44.3	1.35	121.58
Pd (%)	25.9	28.3	32.7	23.9	19.1	25	13.3	3.43	84.44
Pc (%)	13.6	23.2	14.1	6.6	2.4	7.1	31.7	3.94	172.69
Pcr (%)	2.2	11.3	11.4	4.4	2.3	4.5	0	0.65	200.00
V_{av} (km/h)	22.48	23.36	16.76	10.98	5.92	18.33	41.92	3.84	150.53
A_{pav} (m/s^2)	0.55	0.26	0.50	0.54	1.17	0.54	0.60	0.70	127.89
A_{nav} (m/s^2)	-0.71	-0.30	-0.52	-0.66	-0.67	-0.59	-1.99	1.25	147.59
N_{rate} (stop/km)	2.67	0.00	1.15	6.02	11.12	2.22	1.27	10.05	200.00
VSP_{max} (W/kg)	15.51	8.22	21.31	12.97	19.63	18.82	9.48	4.20	88.64
VSP_{min} (W/kg)	-23.36	-11.67	-18.76	-11.41	-19.47	-32.26	-31.25	2.20	95.48
VSP_{pav} (W/kg)	3.49	1.75	1.84	2.49	5.30	3.74	4.74	5.16	100.87
VSP_{nav} (W/kg)	-4.40	-2.05	-2.28	-2.85	-2.53	-3.83	-16.90	10.47	156.82
PKE (m/s^2)	0.43	0.27	0.34	0.54	0.71	0.45	0.41	4.32	91.07

Note: (*) only Part 1 for urban driving conditions was used in this study, as mentioned in Table 1; “nav” denotes the average of negative values; “pav” denotes the average of positive values.

As shown in Table 4, seven bus driving cycles show large variability in kinematic parameters, with percentage differences for several indicators exceeding 150-200%. The idling ratio (Pi) ranges from 0.00% (ETC) to 65.4% (NYC), while the stop frequency (Nrate) varies from 0 to 11.12 stops/km, confirming the strong stop-and-go nature of urban cycles. The average speed differs by over 150%, ranging from 5.92 km/h (NYC) to 41.92 km/h (TCOC), which significantly affects combustion efficiency and BC formation. Power-related metrics, such as VSPmax (8.22-21.31 W/kg) and VSPmin (-11.41 to -32.26 W/kg), also exhibit wide gaps, indicating higher transient loads in aggressive cycles.

Compared to others, HBDC represents intermediate conditions typical of Hanoi traffic: moderate speed (16.76 km/h), frequent stops (1.15 stops/km), and balanced acceleration/deceleration. These characteristics make HBDC more representative for local emission modeling than standardized cycles, ensuring accurate BC estimation under Vietnam’s urban conditions.

In the instantaneous emission simulation software, the instant VSP profile is used to compile the distribution of vehicle operation modes, which is then used as unique driving-feature-related input data. This study, therefore, explored the VSP distribution of driving cycles, as shown in Fig. 4.

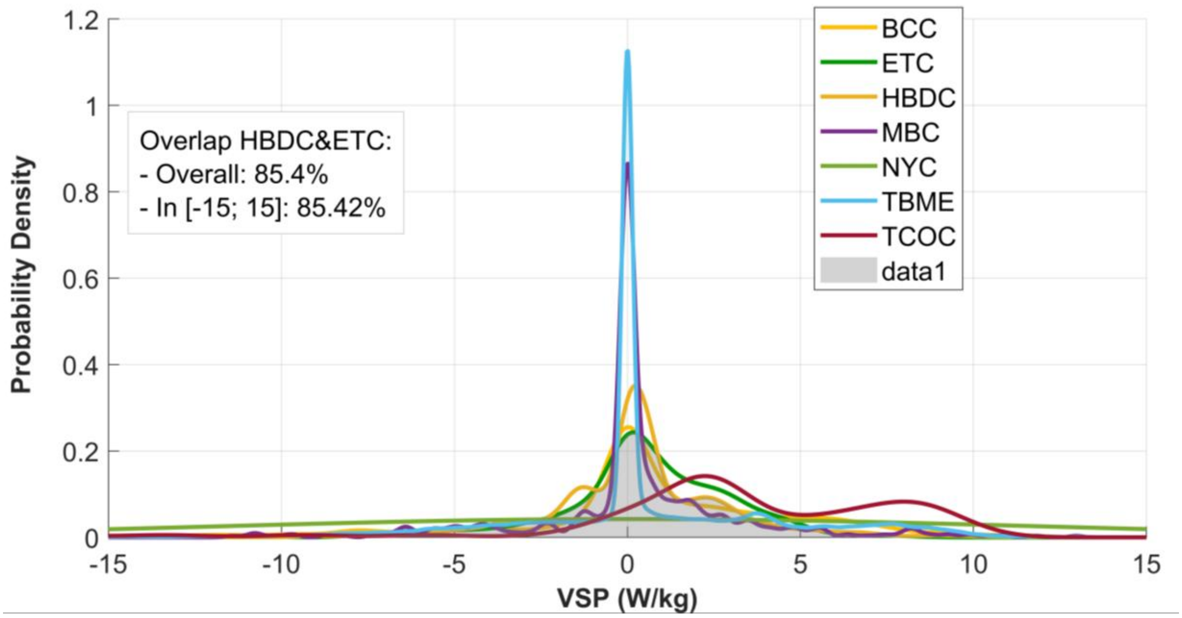

Figure 4. Comparison of the VSP probability density between driving cycles.

(Note: using the Probability Density Function, PDF)

Fig. 4 compares VSP probability density distributions across multiple driving cycles using the Probability Density Function (PDF). The results indicate that all cycles exhibit a pronounced peak near VSP = 0 W/kg, reflecting the dominance of low-power operating conditions such as idling and low-speed cruising in urban traffic environments. Among the cycles, TBME exhibits the highest peak density at zero VSP, indicating a strong concentration of low-power events, which is typical of congested traffic scenarios. The overlap between HBDC and ETC is substantial (85.4% overall; 85.42% within the range [-15, 15] W/kg), suggesting similar power-demand profiles. In contrast, cycles such as TCOC and NYC exhibit wider distributions with secondary peaks, indicating more dynamic driving patterns. These differences highlight the importance of selecting representative cycles for accurate energy and emission modeling.

3.2. Operation modes distribution

The distribution of operating modes (Bins) across the selected driving cycles, as defined by the MOVES model, is shown in Fig. 5. Each Bin represents a combination of instantaneous speed and VSP that characterizes engine load under varying traffic conditions.

As shown in Fig. 5, significant differences in operating mode distributions were observed among the selected driving cycles. In general, urban cycles exhibit high proportions in idling (Bin 1) and low-speed, near-zero VSP ranges (Bins 11-13), reflecting the frequent stop-and-go patterns typical of congested traffic. Notably, Bin 12, representing low-speed conditions, dominates the distribution in all cycles, particularly for ETC (71%) and HBDC (67.2%). At higher speeds, the shift toward Bin 22 is most clearly observed in TCOC (28.2%), followed by BCC (7.5%) and ETC-Part 1 (5.1%). However, TBME is the unique cycle containing high-VSP bins ($\geqslant$ B35), totaling <1% (e.g., B35 $\approx$ 0.39%). This is suitable for TBME, as the cycle is designed for the maximum-energy case.

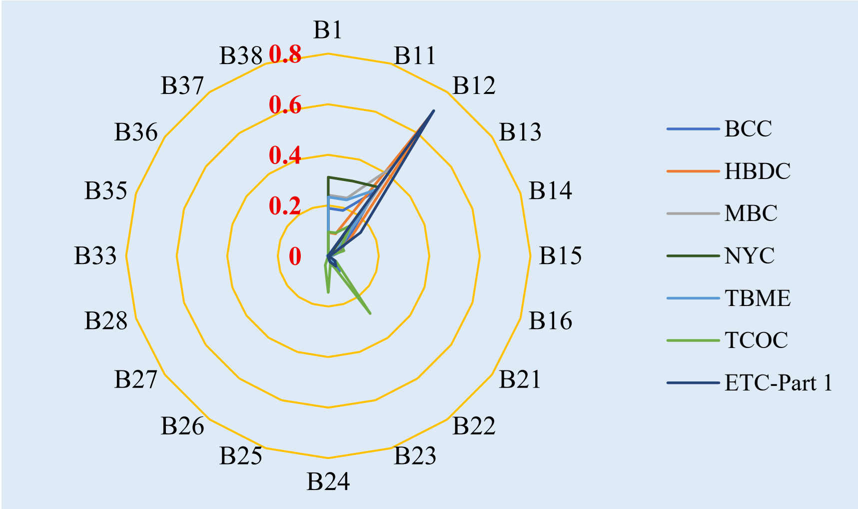

Figure 5. The Bin distribution for operation mode-related selected driving cycles.

For HBDC, the distribution of BINs is mainly concentrated in the range of BINs 12 and 14. This aligns with Hanoi's traffic characteristics, which include moderate average speeds combined with short acceleration phases.

These variations underscore the pivotal role of representative driving cycle selection in emission modeling, as higher-VSP bins (⩾ Bin 24) correspond to aggressive acceleration and high engine loads, which promote incomplete combustion and increase PM and BC emissions [25]. This implies that in higher-VSP bins, the BC emissions from diesel buses are greater.

3.3. Effects of driving cycle on bus' BC emission

Using MOVE-based BC emission simulations driven by driving cycles, this study has determined the BC emission factor in grams per kilometer, as presented in Table 5. In addition, because direct experimental BC emission factors (g/km) for diesel buses are currently unavailable, this study used PM2.5 emission factors and the BC/$PM_{2.5}$ mass fraction as cross-checks to assess the plausibility of our MOVES-based BC estimates.

Table 5. Black carbon emissions from a diesel bus under different driving cycles.

Driving cycles	**$PM_{2.5}$ (g/km)**		**BC (g/km)**	**Mass fraction of BC in $PM_{2.5}$ (%)**	
	This study	Other studies	This study	This study	Other studies
BCC	0.321	0.583 ± 0.451 for the bus fleet in Brisbane [26] 0.580 ± 0.260 for bus China III [27]	0.239	74.4	~ 74.9% for bus China III [27]
ETC	0.340		0.264	77.82	
HBDC	0.427		0.324	76.05	
MBC	0.524		0.379	72.28	
NYC	0.859		0.599	69.76	
TBME	0.355		0.259	73.11	
TCOC	0.256		0.196	76.68	

As shown in Table 5, the $PM_{2.5}$ range obtained in this study (0.256-0.859 g/km) largely overlaps with those of previous studies. For instance, the tunnel study for the Brisbane bus fleet (0.583 ± 0.451 g/km [26]) and the China III bus study (~0.580 ± 0.260 g/km [27]). Furthermore, the BC/$PM_{2.5}$ fractions determined in this study (~70-78%) also closely match the ~74.9%

reported in [27]. These reinforce the reliability of the modeled BC emissions results. The reliability of MOVES has also been reported in previous studies, as noted in Section 2.1. In other words, these consistencies indicate that the MOVES-based simulation approach provides reasonable estimates under real-world driving conditions.

As analyzed in Sections 3.1 and 3.2, urban driving cycles exhibit a large share in Bin 1 (idling) and Bins 11-13 (VSP approximately zero at low-speed ranges), reflecting the stop-and-go characteristics of urban traffic. Cycles with higher proportions in high-VSP bins (⩾ Bin 24, ⩾ Bin 35) are typically associated with sharp acceleration phases, high engine loads, and frequent transient conditions-factors that favor the formation of BC due to incomplete combustion. The results in Table 5 show consistency with the Bin distribution and key kinematic parameters:

- NYC records the highest emissions, with $PM_{2.5}$ of 0.859 g/km and BC of 0.599 g/km. This outcome corresponds to NYC's main share in Bin 1 (up to 31.1%) and Bins 12-13, combined with high VSPmax and Pi, which collectively increase BC content and total $PM_{2.5}$. This is also evident through the aggressive stop-and-go characteristics and prolonged idling periods (up to 65.4%) in this driving cycle. The fact is that prolonged idling also increases PM2.5 and BC emissions from diesel-powered buses, as reported in [28, 29].
- TCOC exhibits the lowest emissions, with $PM_{2.5}$ of 0.256 g/km and BC of 0.196 g/km. This result reflects a clear shift toward Bin 22 (higher speeds and smoother operation) and an almost complete absence of very high VSP bins, reducing transient engine loads. In addition, although this cycle has the highest average speed among those considered, its share of cruising time ranks second, and its maximum VSP value ranks only sixth among the other cycles.
- HBDC shows intermediate values, with $PM_{2.5}$ of 0.427 g/km and BC of 0.324 g/km. This is consistent with its main concentration in Bins 12 and 14: moderate speeds with stop-and-go patterns, but without prolonged aggressive acceleration-characteristic of Hanoi's real traffic conditions.

In summary, driving cycles with extended time in Bin 1 and Bins 11-13, combined with occurrences of high-VSP phases, tend to increase both BC and $PM_{2.5}$ emissions; conversely, increasing the share of Bin 22 and limiting high-VSP bins (⩾ Bin 24) could help reduce BC emissions.

Overall, the results emphasize that optimizing driving patterns-such as reducing idling and aggressive acceleration-could serve as a practical and cost-effective strategy to mitigate BC emissions in contexts where rapid technological upgrades are challenging.

4. CONCLUSIONS

This study employed a model-based approach using the EPA MOVES framework to assess the impact of driving cycles on BC emissions from a representative EURO II diesel bus. Kinematic characteristics, VSP, and operation-mode distributions (Bins), which were used as inputs for assessing, were calculated from seven bus driving cycles.

Key findings indicate that driving cycles with higher proportions of steady-speed bins (Bin 22) and fewer high-VSP events result in reduced BC emissions, whereas driving cycles with longer durations in idling and low-speed bins, as well as frequent high-VSP phases, produce higher BC emissions. As indicated by their different Bin profiles, NYC had the greatest BC emissions (0.599 g/km), TCOC the lowest (0.196 g/km), and HBDC the intermediate (0.324 g/km) among the cycles. The obtained BC results were deemed plausible because BC accounted for approximately 70-78% of $PM_{2.5}$ across all cycles, and the $PM_{2.5}$ range (0.256-0.859 g/km) closely matched published tunnel and on-road measurement results.

The results reconfirm the importance of driving behavior in transport-related emission-reduction strategies. Avoiding aggressive maneuvers, such as rapid acceleration and harsh braking, and maintaining smooth, steady speeds can significantly lower fuel consumption and BC emissions. In Hanoi and other similar areas where rapid technological advancements are challenging, these operational techniques offer an affordable way to reduce BC emissions. Future research could explore integrating eco-driving strategies and intelligent transport systems to further reduce BC emissions under real-world conditions. Additionally, assessing the combined effects of driving patterns and emerging technologies, such as hybridization or electrification of bus fleets, would provide a more comprehensive roadmap for sustainable urban transport. Although the study has provided useful findings, it still has inherent limitations. The scope of this study may be further expanded in future work. Subsequent research could incorporate additional bus technologies or broader real-world conditions to deepen the understanding of how operational patterns influence BC emissions.

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