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The impact of traffic intensity on the performance and efficiency of hybrid electric vehicles

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This paper investigates the impact of traffic congestion on fuel consumption and CO_2 emissions in hybrid electric vehicles (HEVs) operating in urban driving conditions. The analysis encompassed four distinct HEV configurations – PHEV, mixed, MHEV, and split-axle hybrid – and evaluated their performance across five urban routes (T1–T5) exhibiting diverse congestion levels, as well as under the WLTC Low cycle. The data were acquired via simulation using AVL Cruise M, leveraging velocity profiles recorded during peak afternoon traffic. The Monte Carlo method was employed to estimate result variability, yielding 24,000 data points per variable. Findings reveal that PHEVs exhibited the most favorable performance, achieving the lowest fuel consumption (0.00–0.02 l) and CO_2 emissions (0.00–0.05 kg), particularly in stop-and-go urban driving due to their electric operating mode. MHEVs demonstrated the least efficiency, with mixed and split-axle hybrid vehicles performing at an intermediate level. ANOVA and Tukey's post-hoc test statistically validated significant distinctions across HEV types and routes. This research underscores the criticality of real-world testing environments and offers valuable implications for HEV design and the evolution of testing protocols for sustainable urban transportation.

Key words: *hybrid electric vehicle, fuel consumption, CO_2 emission, urban traffic congestion, Monte Carlo simulation*

1. Introduction

Hybrid electric vehicles (HEVs) have emerged as a pivotal component in the global shift towards sustainable transportation, striking a balance between energy efficiency, environmental impact, and economic viability. Compared to purely electric vehicles, HEVs offer significantly extended range and come at a lower cost. When contrasted with conventional internal combustion engine vehicles, they exhibit reduced fuel consumption and substantially lower emissions.

Currently, the market offers various types of hybrid electric vehicles. HEVs integrate an internal combustion engine with an electric powertrain. Plug-in hybrid electric vehicles (PHEVs) incorporate a higher-capacity battery, facilitating external grid charging. A key advantage of PHEVs is their ability to operate solely in electric mode, which significantly reduces fuel consumption. Hybrids demonstrably enhance fuel efficiency and reduce emissions compared to conventional vehicles. This is primarily achieved through the recuperation of kinetic energy during regenerative braking and the optimized operation of the internal combustion engine [5, 8, 10].

In recent years, advancements in battery technology have played a pivotal role in enhancing the energy efficiency of hybrid vehicles. High-performance batteries, characterized by greater energy density and extended lifespans, have enabled hybrid vehicles to achieve superior fuel economy and lower emissions. Moreover, the evolution of lithium-ion batteries has significantly contributed to the overall efficiency of hybrid systems [7, 17].

The efficiency of hybrid vehicles is critically dependent on advanced energy management systems. These systems are designed to optimally distribute power between the internal combustion engine and the electric motor, thereby minimizing energy losses. Strategies such as predictive energy optimization and adaptive control algorithms have been developed to further enhance fuel efficiency and reduce emissions [2, 18].

Hybrid electric vehicles have been the subject of extensive research for years. One of the particularly discussed topics is the issue of harmful exhaust emissions[16, 27]. Studies consistently indicate that vehicles operating under congested traffic conditions can consume up to 30% more fuel compared to those in free-flowing traffic. This increased fuel consumption directly correlates with elevated emissions of carbon dioxide (CO_2), nitrogen oxides (NO_x), and particulate matter (PM) [11, 22, 24]. While studies involving real-world vehicle testing with installed measurement equipment have demonstrated that hybrids can achieve a CO_2 reduction of up to 30% compared to conventional vehicles [14, 19, 21], the environmental benefits of HEV are highly dependent on their specific configuration and driving conditions. For instance, reference [1] investigated the energy consumption of a PHEV under real-world driving conditions over a distance of 12,500 km, analysing the interaction between the internal combustion engine and the electric motor. Instantaneous energy consumption varied from 0.6 to 1.4 MJ/km, with higher values correlating with internal combustion engine operation and consequently, increased CO_2 emissions. Research findings presented in [19] demonstrated that during urban driving, a hybrid vehicle operated solely on its electric motor for 67.70% of the distance travelled and 75.40% of the driving time, leading to a significant reduction in emissions. Furthermore, studies in [3, 4, 6] have indicated that the energy characteristics of both HEVs and PHEVs are highly dependent on various usage conditions, including temperature, trip length, charging frequency, and battery energy capacity. A study [25] analysed vehicle emissions in Toronto and Beijing, demonstrating that hybrid vehicles significantly reduce exhaust emissions compared to conventional vehicles. In Toronto, reductions were observed at 21.6% for CO_2, 31.3% for CO, and 53.0% for NO_x. Beijing showed even greater reductions: 41.0% for CO_2, 28.9% for CO, and 68.5% for NO_x. The more substantial reduction in CO_2 and NO_x emissions in Beijing was attributed to less dynamic driving conditions. The work [12] investigated the fuel consumption of both hybrid and conventional vehicles under real-world conditions. Hybrids demonstrated a significant reduction in fuel consumption at low and medium speeds. It was observed that as speed increased, the differences in fuel consumption between these vehicle types diminished. Conversely, research [15] investigated fuel consumption reductions achieved by hybrid vehicles relative to conventional vehicles under diverse traffic conditions and driving styles in Bangkok. The most substantial fuel consumption reduction for HEVs was noted in urban traffic with smooth driving (approximately 56%), while smaller reductions were observed in suburban and highway driving. Aggressive driving considerably increased fuel consumption in both vehicle types, with HEVs being more susceptible to this driving style in terms of percentage increase in consumption.

Hybrid vehicles, which integrate an internal combustion engine with an electric motor, appear to be a promising solution for urban transportation challenges, particularly in congested conditions like traffic jams. In large cities, especially during peak hours, traffic is characterized by frequent stops and low speeds. Traffic congestion demonstrably leads to increased fuel consumption and elevated emissions of pollutants, including CO_2, NO_x, PM_x, and HC (hydrocarbons), thereby negatively impacting air quality and public health [13, 20]. As evidenced by the previously cited studies, HEVs exhibit significantly lower fuel consumption and emissions in urban environments.

Despite extensive research on hybrid vehicles, a significant gap persists in comprehensive analyses evaluating the impact of real-world traffic congestion on diverse hybrid configurations. Specifically, there's a deficit of studies employing actual road data to compare various hybrid architectures in terms of fuel consumption and emissions. Previous work has often been limited to general assertions about the necessity of urban-centric analyses, without precisely defining the specific knowledge gaps that could be addressed.

In response to the identified research gap, this study utilizes real-world velocity profiles, derived from actual driving data, to simulate the operation of four distinct hybrid vehicle types under varying urban congestion conditions. This methodology enables a more detailed assessment of their operational parameters and the optimization of powertrain management strategies in the context of contemporary urban challenges. The primary objective of this research is to quantitatively evaluate how different levels of traffic congestion impact key hybrid vehicle parameters, specifically fuel consumption and CO_2 emissions. The findings are expected to provide valuable insights for both powertrain designers and policymakers regarding the improvement of urban transportation efficiency.

This study addresses this gap by providing analyses based on real-world velocity profiles from congested urban environments. This approach will allow for a more precise evaluation of the efficiency of hybrid powertrain vehicles in congested urban conditions and enable better adaptation of powertrain control strategies to the realities of contemporary cities. This research, therefore, not only aligns with the current understanding in the field but also contributes to addressing global challenges concerning transportation, climate change, and urbanization.

2. Experimental methods

2.1. Real-world data acquisition

Real-world urban driving testing aimed to acquire velocity profiles of a representative vehicle, enabling the modeling of typical driving scenarios in highly congested areas. A precise Kistler GPS Data Logger was used to record motion parameters such as instantaneous velocity, longitudinal acceleration, time, and geographical coordinates. This logger offers high measurement accuracy (10 Hz sampling frequency, GPS position accuracy < 2.5 m), ensuring the reliability of the collected data.

The data acquisition process was conducted along five distinct urban routes (T1–T5) situated within an European medium-sized city (Kielce, Poland). These routes were chosen to encompass a variety of driving conditions, including frequent stops at intersections, fluctuating speeds in urban traffic, and segments with smoother flow. Each route was approximately 5 km in length, which allowed for the collection of representative data relevant to typical urban commutes. Measurement data were gathered during the afternoon rush hour (3:00 PM–5:00 PM), a period characterized by the highest traffic intensity and significant congestion, accurately reflecting the real-world challenges of urban transportation. As an example, the velocity (v) and longitudinal acceleration (a) profiles as a function of time for route T2 are presented in the Fig. 1.

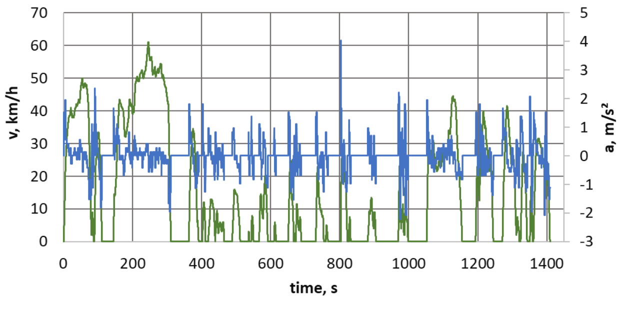

Fig. 1. Velocity (v) and acceleration (a) profiles for route T2

The collected velocity profiles served as input data for simulation studies in AVL Cruise M software. The goal of these simulations was to estimate fuel consumption and CO_2 emissions on the selected urban routes, and to compare them against the standard WLTC Low cycle.

2.2. Modelling and simulation studies in AVL Cruise M

Simulation studies were conducted using AVL Cruise M software, an advanced tool designed for the analysis of vehicle powertrains. This software allows for detailed modeling of vehicle dynamics, energy consumption, and exhaust emissions based on specified driving cycles. For the comparative evaluation of four hybrid vehicle types in this study, AVL Cruise M was employed. The following configurations were analyzed: plug-in hybrid electric vehicles (PHEV), mild hybrid electric vehicles (MHEV), series-parallel hybrid (mixed), and split-axle hybrid, where the internal combustion engine powers the front axle and the electric drive powers the rear axle. Selected technical parameters of the analyzed vehicles are presented in Table 1.

Table 1. Technical specifications of selected hybrid vehicle types

Parameter		PHEV	mixed	MHEV	split-axle hybrid
Inernal Combustion Engine	Engine displacement, cm^3	1800	1800	1800	2478
	Number of cylinders	4	4	4	4
	Engine inertia, kg·m^2	0.1	0.18	0.18	0.18
	Engine stall speed, rpm	500	500	500	500
	Maximum engine speed, rpm	6500	6500	6500	6000
Battery	Minimum voltage, V	123	240	37	37
	Maximum voltage, V	184	360	54	54
	Maximum charge, Ah	20	20	20	20
	Initial state of charge, %	80	50	50	50
Electric motor	Maximum motor torque, N·m	180	55	63.4	153.6
	Maximum motor power, kW	56.55	15	9.25	24.63
	Speed at maximum motor torque, rpm	0	0	0	0
	Speed at maximum motor power, rpm	3000	4000	2707	3500
	Maximum generator torque, N·m	172.5	55	60.8	152.96
	Maximum generator power, kW	54.64	15	4.62	24.13

The objective of this study is to assess the potential of various hybrid vehicle configurations within the context of sustainable transportation. To achieve this, four HEV types were selected, each characterized by a distinct degree of electric powertrain involvement in delivering power to the wheels and facilitating vehicle movement. This involvement directly influences fuel consumption and CO_2 emissions. Understanding the efficiency and benefits of these configurations under diverse operating conditions is a crucial element of this analysis. The PHEV, equipped with a high-capacity battery and external charging capability, allows a significant portion of the journey to be completed solely in electric mode. This configuration offers the lowest fuel consumption, directly translating to reduced emissions. In contrast, the MHEV features a minimal degree of electrification, where an electric motor (typically an integrated starter-generator, or ISG) primarily assists the internal combustion engine (ICE) during start up and acceleration. It also enables regenerative braking to recover energy into a small-capacity battery. The ICE's contribution remains dominant throughout the vehicle's operation, and pure electric driving is generally not possible or limited to very short distances and low speeds. Figure 2 presents the MHEV vehicle model in AVL Cruise M.

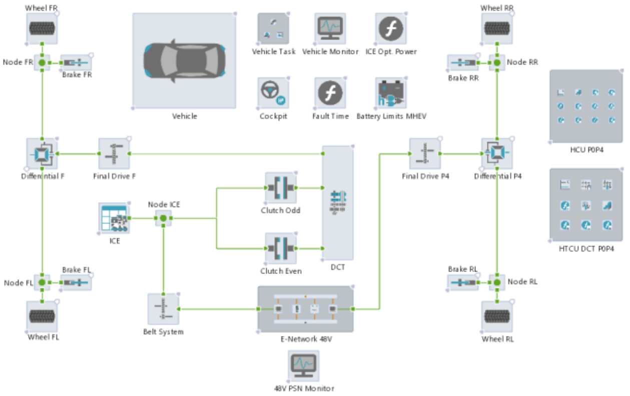

Fig. 2. MHEV vehicle model in AVL Cruise M

The series-parallel (mixed) configuration, also known as a full hybrid, allows for independent or combined operation of both the internal combustion engine and the electric motor in delivering torque to the powertrain. This enables all-electric driving for short distances and at lower speeds. Regardless of traction conditions, the internal combustion engine operates within its optimal range, assisting the electric motor during acceleration while continuously charging the battery. This configuration facilitates a more significant reduction in fuel consumption and emissions through regenerative braking and electric assistance.

The split-axle configuration is characterized by a drivetrain separation where one axle (typically the front) is powered by an internal combustion engine, while the other (the rear) is driven by an electric motor. This setup allows for single-axle or all-wheel drive operation depending on driving conditions and power demand, with the internal combustion engine generally playing a dominant role.

To accurately reflect real-world driving conditions, the simulations incorporated velocity profiles collected from five distinct routes, designated T1–T5. These profiles were derived from actual data gathered in urban and suburban environments, allowing for the inclusion of diverse traffic conditions such as frequent stops, fluctuating speeds, and varying traffic densities. Additionally, to provide a reference point for standardized testing, the Worldwide Harmonized Light Vehicles Test Cycle (WLTC) Low was included as a comparative benchmark.

Within the AVL Cruise M environment, each vehicle type was subjected to simulations across six driving cycles (T1–T5 and WLTC Low). These simulations were configured to record key analytical parameters: fuel consumption and CO_2 emissions. These parameters are crucial for assessing the environmental impact and operational efficiency of the vehicles. The collected data were subsequently analysed to evaluate how each hybrid vehicle type performed under varying driving conditions. This comprehensive approach allowed for a comparative analysis of the four HEV types, providing quantitative data on their relative operational characteristics and limitations in both real-world conditions and defined test cycles.

2.2. Assessing fuel consumption and CO_2 emission variability using Monte Carlo simulation

To overcome the limitations of single observations for each hybrid powertrain type and route profile combination, a Monte Carlo simulation was employed. This method enabled the generation of synthetic data based on the original measurements. This approach allowed for the assessment of differences in fuel consumption and CO_2 emissions among the four HEV types (PHEV, mixed, MHEV, split-axle hybrid) and the six test routes (T1–T5, WLTC Low).

Fuel consumption and CO_2 emissions for each HEV type and route combination were modeled using a gamma distribution. This choice is justified by the gamma distribution's effectiveness in describing non-negative and skewed data, which is characteristic of fuel consumption and emission measurements. The parameters of the gamma distribution, specifically shape (α) and scale (β), were calculated based on the mean (μ), equal to the observed value, and an assumed standard deviation (σ), according to the following equations:

$$\alpha = \left(\frac{\mu}{\sigma}\right)^2 \tag{1}$$

$$\beta = \frac{\sigma^2}{\mu} \tag{2}$$

In instances where $\mu=0$, a minimum standard deviation of $\sigma = 0.001$ was assumed. This guarantees a positive variance, enabling sample generation. In the baseline scenario, the following assumptions were made:

$$\sigma = 0.1 \cdot \mu \tag{3}$$

This approach reflects the typical variability in this type of data in the absence of empirical repetitions. To verify the impact of this assumption, a sensitivity analysis was conducted for alternative values:

$$\sigma = 0.05 \cdot \mu \tag{4}$$

and

$$\sigma = 0.2 \cdot \mu \tag{5}$$

For each of the 24 combinations (4 HEV types × 6 routes), 1000 simulated observations were generated, resulting in a total of 24,000 data points for each variable (fuel consumption and CO_2 emissions). This number of simulations ensured sufficient data for subsequent statistical analyses.

The Monte Carlo simulation process was conducted using the R programming language and involved the following stages:

1. For each combination of HEV type and route, 1000 values for fuel consumption and CO_2 emissions were generated from a gamma distribution with parameters α and β.
2. Mean values and 95% confidence intervals were computed for the simulated data, enabling the estimation of result variability.
3. A two-way analysis of variance (ANOVA) was performed, including an interaction term between HEV type and route, to assess the statistical significance of differences in fuel consumption and CO_2 emissions.
4. Tukey's post-hoc test was then applied to identify specific differences among HEV types and individual routes.

Additionally, a sensitivity analysis was conducted to assess the impact of the assumed standard deviation on the results. Three values of $\sigma \in \{0.05\ \mu, 0.10\ \mu, 0.20\ \mu\}$ were tested, and the resulting ANOVA outcomes and confidence intervals were compared. This analysis allowed for an evaluation of the stability of the conclusions based on the assumed level of data variability. The findings presented in [9, 22, 25] suggest that the chosen σ values in the Monte Carlo simulations are justified to reflect a realistic range of variability for fuel consumption and CO_2 emissions.

3. Results

3.1. Comparison of real-world route parameters and WLTC Low Test

Data for the analysis were collected from five real-world driving cycles (T1–T5). These cycles were conducted under typical urban conditions, characterized by heavy congestion, frequent stops, and variable traffic. Additionally, the WLTC Low phase was included as a standard reference cycle. The mean and maximum values of velocity and acceleration, along with stop times, were estimated. A summary of the selected route parameters is presented in Table 2.

Table 2. Summary of selected route parameters

Route/ Parameter	T1	T2	T3	T4	T5	WLTC Low
Duration, s	685	1409	780	1135	1022	589
Stop duration, s	99	594	129	339	138	146
Share of idling in total travel time, %	14%	42%	17%	30%	14%	25%
Max. velocity, km/h	56	61	61	51.5	54	56.9
Mean velocity w/o stops, km/h	35.17	25.08	29.7	26.78	24.4	25.7
Mean velocity w/ stops, km/h	30.09	14.51	24.79	18.78	21.11	18.9
Min. acceleration, m/s^2	–3.61	–2.22	–2.92	–3.06	–2.92	–1.47
Max. acceleration, m/s^2	3.61	4.03	2.36	2.64	2.78	1.47

In the T1–T5 cycles, maximum velocity range from 51.5 km/h (T4) to 61 km/h (T2 and T3), whereas the WLTC Low cycle exhibits a maximum velocity of 56.9 km/h. Average velocity, including stops, varies significantly across the urban cycles, from 14.51 km/h (T2) to 30.09 km/h (T1), compared to 18.9 km/h in WLTC Low. Excluding stops, these values increase; for instance, T1 rises to 35.17 km/h and WLTC Low to 25.70 km/h.

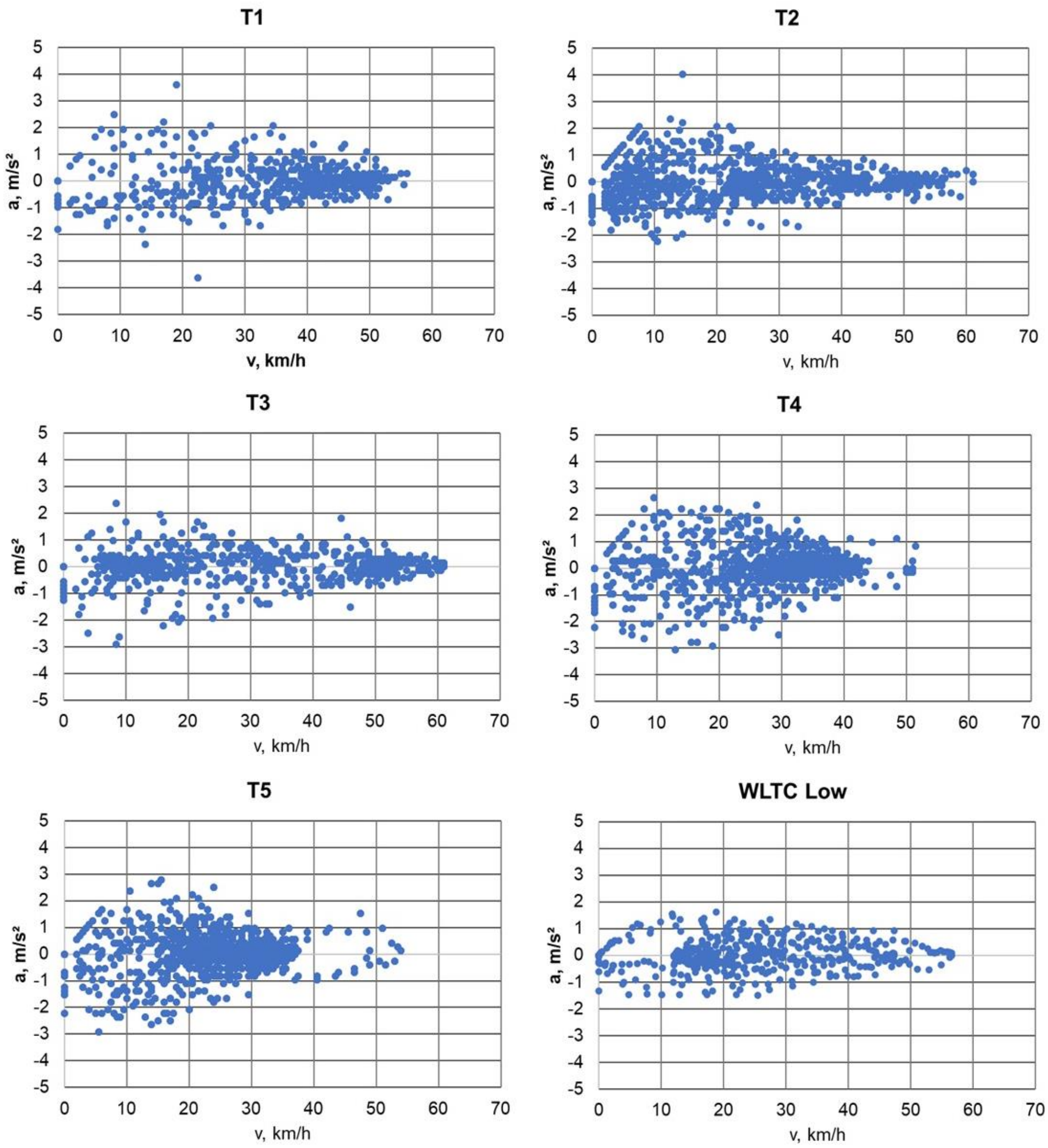

Fig. 3. Distribution of longitudinal accelerations (a) and velocities (v) in analyzed cycles

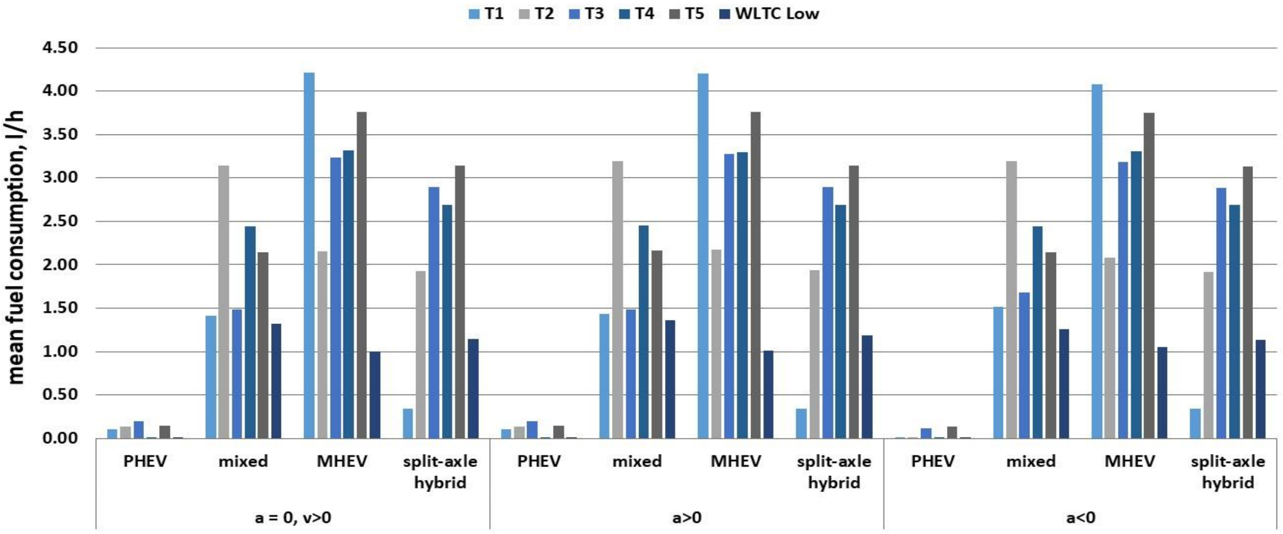

Fig. 4. Mean fuel consumption across selected driving phases

The velocity profiles as a function of time of selected routes show numerous brief accelerations after stops, contrasting with the smoother profile of WLTC Low. Figure 3 illustrates the recorded longitudinal accelerations (a) across the analysed cycles, highlighting the considerable diversity in the results. Notably, the WLTC Low cycle shows the smallest range of longitudinal acceleration values.

The T1–T5 cycles demonstrate greater variability than the WLTC Low: lower average velocity with stops (e.g., 14.51 km/h in T2 vs. 18.9 km/h in WLTC Low), higher maximum accelerations (up to 4.03 m/s^2 vs. 1.47 m/s^2), and a larger proportion of idle time (up to 42% in T2 vs. 25% in WLTC Low). These discrepancies suggest that standard test profiles, such as the WLTC Low, do not fully capture real-world urban driving conditions. Data from T1–T5 can therefore be instrumental in designing vehicles optimized for energy consumption, fuel efficiency, and emissions.

3.2. Analysis of fuel consumption for different HEV types in congested conditions

The initial analysis focused on the fuel consumption values obtained by the selected HEV types across each of the T1–T5 routes and in the WLTC Low test. Table 3 presents the fuel consumption (in liters) for four types of hybrid powertrains over five highly congested urban drives (T1–T5) and in the WLTC Low cycle.

Table 3. Summary of fuel consumption [l] for selected hybrid vehicle types

Route/ HEV type	T1	T2	T3	T4	T5	WLTC Low
PHEV	0.01	0.02	0.02	0.00	0.02	0.00
mixed	0.12	0.52	0.15	0.32	0.25	0.09
MHEV	0.33	0.36	0.30	0.44	0.45	0.08
split-axle hybrid	0.28	0.33	0.28	0.37	0.36	0.07

Plug-in Hybrid Electric Vehicles (PHEV) consistently demonstrated the lowest fuel consumption, ranging from 0 to 0.02 l in urban tests and 0.00 l in the WLTC Low cycle. This highlights the predominant use of electric propulsion, given an initial battery state of charge (SOC) of 80%. The series-parallel (mixed) hybrid consumed between 0.12 l and 0.52 l in urban traffic and 0.09 l in the WLTC Low cycle. Mild Hybrid Electric Vehicles (MHEV), featuring a smaller electric motor assisting the internal combustion engine, exhibited higher fuel consumption (0.30–0.45 l in urban tests). However, they achieved 0.00 l in the WLTC Low cycle due to the significant proportion of idle time within that cycle and the capability for temporary engine shutdown. The split-axle hybrid, with an internal combustion engine on the front axle and an electric motor on the rear, consumed between 0.28 l and 0.37 l on urban routes and 0.07 l in the WLTC Low cycle. This indicates good recuperation efficiency, though its overall fuel efficiency is surpassed by PHEVs. Table 4 shows the fuel consumption in liters per km for four types of hybrid powertrains over five highly congested urban drives (T1–T5) and in the WLTC Low cycle.

Differences in fuel consumption between real-world routes and the WLTC Low cycle emphasize the importance of accounting for high congestion in testing. PHEVs appear to be the most efficient in urban conditions, particularly on routes with frequent stops, such as T2. These results unequivocally demonstrate that the level of hybridization and the drivetrain architecture are pivotal factors influencing fuel consumption in highly congested urban driving conditions.

Table 4. Summary of fuel consumption [l/km] for selected hybrid vehicle types

Route/ HEV type	T1	T2	T3	T4	T5	WLTC Low
PHEV	0.002	0.003	0.004	0.000	0.003	0.000
mixed	0.024	0.104	0.031	0.065	0.051	0.025
MHEV	0.066	0.073	0.060	0.087	0.091	0.053
split-axle hybrid	0.056	0.065	0.057	0.073	0.072	0.021

Based on the data presented in Table 4, significant differences in fuel consumption were observed across the selected hybrid vehicle types. As evidenced by the results, the PHEV consistently demonstrated the lowest fuel consumption, with values approaching zero in the T4 and WLTC Low routes, highlighting its superior efficiency in these specific conditions. In contrast, both MHEV and the split-axle hybrid exhibited higher fuel consumption across all routes, with the mixed hybrid showing the most varied performance, including the highest consumption value of 0.104 l/km in the T2 route. The data clearly indicates that the PHEV's design allows it to achieve substantially lower fuel consumption per kilometer compared to the other hybrid architectures, particularly under specific driving conditions.

To analyse fuel consumption across various traffic phases, instantaneous data were categorized into three groups: acceleration ($a > 0$), constant speed driving ($a \approx 0$), and braking ($a < 0$). Figure 4 presents the mean fuel consumption values (in l/h) during each traffic phase on selected routes.

During the constant speed driving phase ($a = 0$, $v > 0$) on routes T4 and WLTC Low, the PHEV does not utilize its internal combustion engine. On the remaining routes, low mean fuel consumption values, ranging from 0.11 to 0.20 l/h, were recorded. The other HEV types exhibit fuel consumption during the constant speed phase. The mixed hybrid consumes from 0.59 l/h (T1) to as much as 1.31 l/h (T2), the MHEV from 0.86 l/h (T2) to 1.75 L/h (T1), and the split-axle hybrid from 0.80 l/h (T2) to 1.49 l/h (T1). This consumption is attributed to the continuous operation of the internal combustion engine during this driving phase.

During acceleration ($a > 0$), particularly at high acceleration rates, the PHEV necessitated the cooperation of both powertrains. The maximum mean fuel consumption in this phase for PHEV was 0.083 l/h on route T3. The other hybrid types required the internal combustion engine to operate during acceleration on all urban routes. It can be observed that the fuel consumption value is dependent on the level of hybridization. For the series-parallel (mixed) configuration, the range of mean values on real-world speed profiles was from 0.60 l/h (T1) to 1.329 l/h (T2). For MHEV, where the electric drive only assists the internal combustion engine, mean fuel consumption values ranged from 0.91 l/h (T2) to 1.750 l/h (T1). In the case of the split-axle hybrid, where the internal combustion engine is the primary energy source, this range was from 0.81 l/h to 1.492 l/h (T1).

During the deceleration phase ($a < 0$), the PHEV recorded low fuel consumption values on cycles T3 and T5, specifically 0.05 l/h and 0.06 l/h, respectively. The other hybrid vehicles exhibited fuel consumption in every analysed driving cycle. The mixed hybrid maintained mean fuel consumption values between 0.63–1.330 l/h, the MHEV between 0.87–1.70 l/h, and the split-axle between 0.80–1.49 l/h.

During the idle phase, fuel consumption in hybrid vehicles is contingent upon their ability to shut down the internal combustion engine. Figure 5 illustrates the mean fuel consumption values recorded by the analysed HEV types while idling.

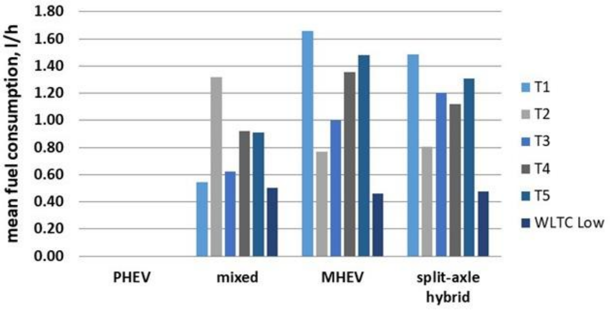

Fig. 5. Mean fuel consumption at idle ($v = 0$)

In every urban route and the WLTC Low cycle, the PHEV exhibits zero fuel consumption at idle. Its substantial battery capacity and full-electric mode capability make it the most efficient HEV type for conditions with frequent stops, notably in routes like T2 and T4.

Conversely, the MHEV consumes fuel while idling on urban routes. The highest mean idle fuel consumption was observed on route T1, reaching 1.66 l/h, while the lowest was 0.77 l/h on route T2. This can be attributed to the electric drive primarily assisting the internal combustion engine during periods of high power demand. However, when the battery's SOC falls to a predetermined lower limit, the ICE additionally provides power to recharge the battery.

In the WLTC Low cycle, the mean idle fuel consumption was significantly lower than that observed in the real-world speed profile cycles, amounting to 0.46 l/h. The mixed hybrid exhibited fuel consumption at idle across all tests. The lowest mean fuel consumption for the mixed hybrid was recorded in T1 at 0.55 l/h, while the highest was in T2 at 1.32 l/h. Lacking external charging capability, series-parallel hybrids power their electrical system exclusively through regenerative braking or the internal combustion engine. Consequently, if the SOC is low, the internal combustion engine is activated even at idle to recharge the battery. In contrast to series-parallel hybrids, split-axle hybrids do not possess the ability to shut down the internal combustion engine at idle. In split-axle hybrids, the internal combustion engine powers one axle, typically the front, and the electric motor drives the other axle, usually the rear. Crucially, there is no direct mechanical connection between these two drives. The mean fuel consumption for split-axle hybrids across the analysed routes ranged from 0.81–1.49 l/h.

In real-world urban conditions, where idle time ranges from 14% to 42%, PHEVs distinguish themselves as the most fuel-efficient HEV type during idling periods. Their capability for exclusive electric-mode operation eliminates fuel consumption in this phase, which is critical in congested urban areas. MHEVs exhibit variable efficiency, demonstrating lower effectiveness on urban routes but higher efficiency in the WLTC Low cycle. Mixed and split-axle hybrids are less effective in reducing fuel consumption at idle, underscoring the importance of designing hybrid systems specifically optimized for electric mode operation under such conditions.

3.3. Investigation of CO_2 emissions for different HEV types in congested conditions

This section of the study analyzes CO_2 emissions from various hybrid vehicle types across five real-world urban routes with high congestion (T1–T5), as well as in the standardized WLTC Low cycle. Table 4 presents the total CO_2 emissions (in kilograms) for each hybrid type on routes T1–T5 and in the WLTC Low cycle.

Table 5. Summary of CO_2 emissions [kg] for selected hybrid vehicle types

Route/ HEV type	T1	T2	T3	T4	T5	WLTC Low
PHEV	0.02	0.04	0.05	0.00	0.04	0.00
mixed	0.29	1.25	0.37	0.78	0.61	0.21
MHEV	0.79	0.87	0.72	1.05	1.09	0.33
split-axle hybrid	0.67	0.79	0.68	0.88	0.86	0.18

PHEV consistently exhibited the lowest CO_2 emissions across all examined scenarios. On urban routes, emissions ranged from 0 kg (T4) to 0.05 kg (T3), while in the WLTC Low cycle, reaching zero was assumed. These minimal values are attributed to the PHEV's capability for all-electric operation, which is particularly effective for short distances and in conditions with frequent stops. On route T4, characterized by a high proportion of idle time, the electric propulsion entirely eliminated CO_2 emissions, confirming the high efficiency of PHEV in congested urban environments.

The mixed hybrid recorded CO_2 emissions ranging from 0.29 kg (T1) to 1.25 kg (T2) on urban routes, with a value of 0.21 kg in the WLTC Low cycle. The highest emission on route T2 can be attributed to the longer duration of the drive and a significant proportion of idle time, necessitating more frequent operation of the internal combustion engine. In the WLTC Low cycle, the smoother driving profile resulted in significantly lower emissions, indicating greater efficiency for this powertrain type under controlled conditions compared to real-world urban traffic.

MHEVs exhibited the highest CO_2 emissions on urban routes, ranging from 0.72 kg (T3) to 1.09 kg (T5), yet demonstrated zero emissions (0.00 kg) in the WLTC Low cycle. The elevated values in urban conditions stem from their limited electric-mode capability and smaller battery capacity, leading to more frequent internal combustion engine engagement, particularly during dynamic accelerations. The zero emissions in the WLTC Low cycle suggest the effectiveness of the engine stop-start function under stable test conditions, a benefit that does not fully translate to real-world urban traffic.

The split-axle hybrid demonstrated CO_2 emissions ranging from 0.67 kg (T1) to 0.88 kg (T4) on urban routes, and 0.18 kg in the WLTC Low cycle. This powertrain architecture allows for a degree of flexibility in energy management, positioning it between the mixed hybrid and PHEV in terms of CO_2 emission levels. The lower emissions observed in the WLTC Low cycle, as compared to urban routes, suggest better adaptation to smooth traffic flow rather than congested conditions.

This study revealed that PHEVs are the most environmentally friendly HEV type in urban conditions, generating minimal or zero CO_2 emissions due to their electric propulsion. Mixed and split-axle hybrids demonstrated moderate results, whereas MHEVs, owing to their limited energy flexibility, generated the highest CO_2 emissions in urban traffic. The discrepancies between the results on urban routes and the WLTC Low cycle underscore the significant impact of real-world driving conditions on CO_2 emissions. This suggests the necessity of developing more realistic testing standards for evaluating the environmental performance of hybrid vehicles. Table 6 shows the total CO_2 emissions per km for each hybrid type on routes T1–T5 and in the WLTC Low cycle.

Table 6. Summary of CO_2 emissions [kg/km] for selected hybrid vehicle types

Route/ HEV type	T1	T2	T3	T4	T5	WLTC Low
PHEV	0.005	0.008	0.009	0.000	0.008	0.000
mixed	0.058	0.250	0.074	0.155	0.122	0.059
MHEV	0.158	0.175	0.145	0.210	0.218	0.125
split-axle hybrid	0.134	0.157	0.137	0.176	0.173	0.050

Based on the data presented in Table 6, significant differences in CO_2 emissions were observed across the selected hybrid vehicle types. Consistent with its fuel consumption, the PHEV demonstrated the lowest CO_2 emissions, with values approaching zero in the T4 and WLTC Low routes, highlighting its superior environmental performance in these specific conditions. In contrast, both the MHEV and the mixed hybrid consistently exhibited the highest emission rates, with the MHEV reaching a peak of 0.218 kg/km on route T5. The data clearly indicate that the PHEV's operational mode allows it to achieve substantially lower CO_2 emissions per kilometer compared to the other hybrid configurations.

Subsequently, the mean CO_2 emissions in kg/h were analysed. These measurements were taken across five real-world urban routes (T1–T5) and in the standardized WLTC Low cycle, considering three distinct driving phases: constant speed ($a = 0$, $v > 0$), acceleration ($a > 0$), and braking ($a < 0$). The average CO_2 emission values for the vehicles analysed are presented in Fig. 6.

During constant speed driving, PHEVs exhibit the lowest CO_2 emissions, ranging from 0.00–0.20 kg/h, primarily due to their electric mode capability. The mixed hybrid shows higher emissions, from 1.32–3.15 kg/h, indicating more frequent use of the internal combustion engine. MHEVs generate the highest emissions, at 1.00–4.22 kg/h, attributed to their limited electric support. The split-axle hybrid achieves intermediate values, from 0.34–3.14 kg/h, reflecting the moderate efficiency of its split powertrain.

During acceleration, CO_2 emissions generally increase. PHEVs continue to emit the least, ranging from 0.00–0.20 kg/h, which confirms the efficiency of their electric powertrain. The mixed hybrid shows higher values, from 1.36–3.19 kg/h, due to increased load on the internal combustion engine during intense acceleration. MHEVs generate the highest mean emissions, at 1.01–4.20 kg/h, indicating limited electric drive support. The split-axle hybrid exhibits intermediate values, from 0.34–3.14 kg/h, with emissions tending to rise under more demanding conditions.

During the deceleration phase, thanks to braking regeneration, CO_2 emissions are generally lower than during acceleration. PHEV again achieves minimal values, ranging from 0.00–0.13 kg/h, which indicates a significant contribution from the electric mode during driving in each cycle. The mixed hybrid shows higher emissions, from 1.26–3.19 kg/h, with a maximum on T2. MHEVs are characterized by the highest values, from 1.05–4.08 kg/h, indicating limited emission reduction capabilities in this phase. The split-axle hybrid falls in between, at 0.35–3.14 kg/h, offering moderate efficiency.

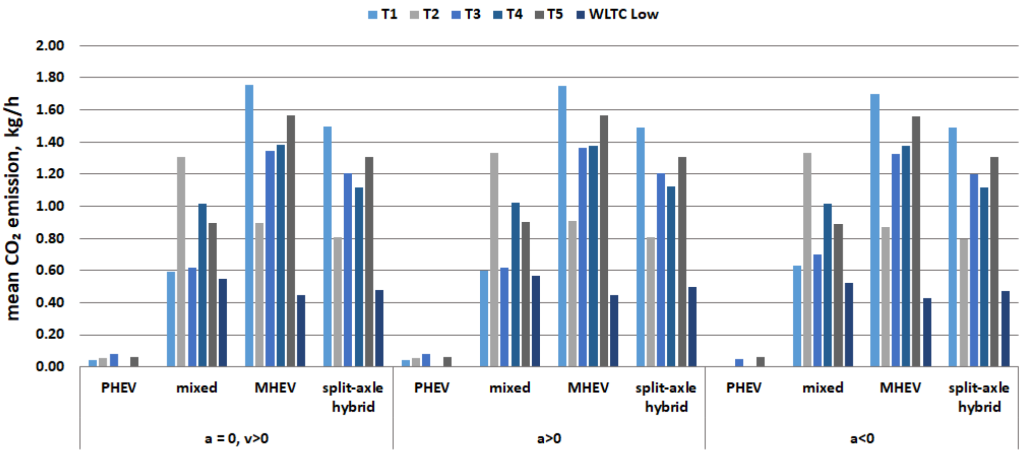

Fig. 6. Mean CO_2 emissions across selected driving phases

Idling, a significant aspect of urban traffic, is a crucial parameter in assessing the ecological performance of HEVs, as different hybrid technologies demonstrate varying capacities for emission reduction during this phase. The Fig. 7 presents the average CO_2 emission values across five cycles with velocity profiles gathered during real-world urban driving conditions and in the WLTC Low cycle.

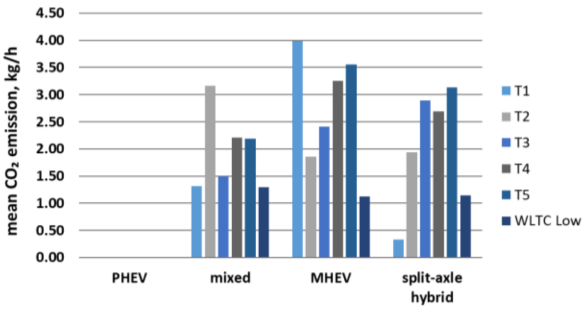

Fig. 7. Mean CO_2 emissions at idle (v = 0)

Analysis of CO_2 emissions during idle periods revealed significant differences among hybrid types. The PHEV consistently emitted 0.00 kg/h across all routes (T1–T5) and in the WLTC Low cycle, underscoring the efficiency of its electric powertrain and its capacity for complete internal combustion engine switch off, which is particularly advantageous in urban driving conditions. The mixed hybrid exhibited varied emissions, ranging from 1.31–3.16 kg/h on T1–T2, yet 0.00 kg/h in the WLTC Low cycle. This variation indicates the internal combustion engine's activity in real-world urban conditions during idling, likely for battery recharging purposes. The MHEV generated the highest emissions, from 1.85–3.98 kg/h on T2-T1, and 1.12 kg/h in the WLTC Low cycle. This is attributed to its limited ability to switch off the ICE.

3.4. Estimating variability in hybrid vehicle fuel consumption and CO_2 emissions using Monte Carlo simulation

This subsection presents the results of a study on the variability of fuel consumption and CO_2 emissions across the 4 analyzed hybrid vehicle types. The analysis was conducted using the Monte Carlo simulation method, which allowed for the estimation of these parameters under various test routes (T1–T5 and WLTC Low) despite a limited number of empirical data points. The results encompass mean values, confidence intervals, and statistical analysis, enabling the evaluation of differences between vehicle types and routes. For each combination of hybrid powertrain and route, 1000 observations were generated, yielding a total of 24,000 data points for each variable (fuel consumption and CO_2 emissions). ANOVA results demonstrated statistically significant effects for both fuel consumption and CO_2 emissions across all analyzed scenarios.

The simulated fuel consumption results, including mean values and 95% confidence intervals for selected vehicle type and route combinations, are presented in Fig. 8.

Analysis of variance revealed statistically significant differences in fuel consumption between vehicle types and routes. For $\sigma = 0.05$, the main effect of HEV type was highly significant, as confirmed by an F-value of 613193 ($p < 0.001$). This indicates substantial variations in fuel consumption among the different hybrid vehicle types. The route effect was also statistically significant, with an F-value of 211648 ($p < 0.001$), underscoring the considerable impact of driving conditions on fuel consumption.

The interaction between HEV type and route was also statistically significant (F = 48,779, $p < 0.001$), suggesting that the effectiveness of individual HEV types is dependent on the specific characteristics of the route. As σ increased to 0.1, the F-statistics decreased, but the effects remained significant: for HEV type, F = 151,279 ($p < 0.001$); for route, F = 52,342 ($p < 0.001$); and for the interaction between hybrid type and route, F = 12076 ($p < 0.001$). For $\sigma = 0.2$, the F-values were F = 37,950 ($p < 0.001$) for HEV type, F = 13,084 ($p < 0.001$) for route, and F = 3073 ($p < 0.001$) for the interaction between route and hybrid type, respectively. These consistent values confirm the stability of the obtained results.

Table 5 presents the results of Tukey's post-hoc test, comparing the mean differences in CO_2 emissions among hybrid powertrain types. It includes the mean difference, the lower and upper bounds of the 95% confidence interval (CI), and the adjusted p-value, where $p < 0.05$ indicates a significant difference.

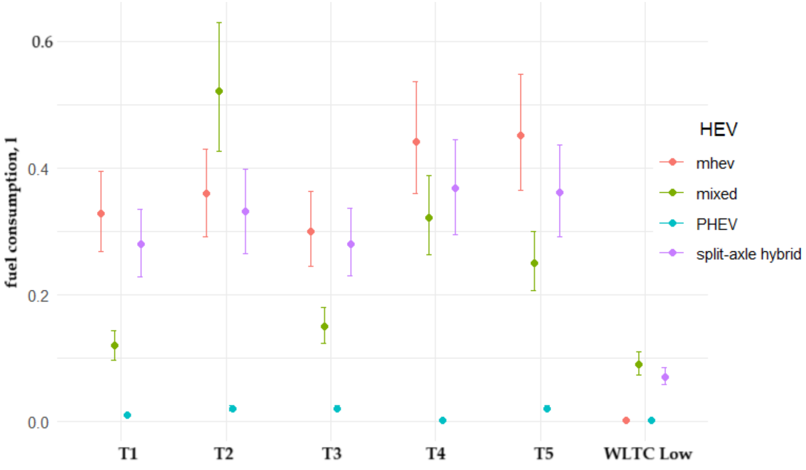

Fig. 8. Distributions of fuel consumption [l] with 95% confidence intervals for $\sigma = 0.1$

Table 5. Tukey's post-hoc test results for fuel consumption differences [l] among hybrid vehicle types

Parameter	Mean difference	Lower CI	Upper CI	p-value
mixed – MHEV	–0.071	–0.074	–0.069	< 0.001
PHEV – MHEV	–0.302	–0.304	–0.299	< 0.001
split-axle hybrid – MHEV	–0.031	–0.034	–0.029	< 0.001
PHEV – mixed	–0.230	–0.233	–0.228	< 0.001
split-axle hybrid – mixed	0.040	0.037	0.042	< 0.001
split-axle hybrid – PHEV	0.270	0.268	0.273	< 0.001

Tukey's post-hoc test revealed statistically significant differences in fuel consumption between all pairs of HEV types ($p = 0$). The most substantial difference was observed between PHEV and MHEV (mean difference: –0.3015 l, 95% CI: [–0.3041, –0.2990]), indicating that PHEV consumes significantly less fuel than MHEV. PHEV also differed significantly from mixed hybrid (mean difference: -0.2304 l, 95% CI: [–0.2329, –0.2278]) and split-axle hybrid (mean difference: 0.2701 l, 95% CI: [0.2676, 0.2727]), demonstrating the lowest fuel consumption among all types. The mixed hybrid consumed less fuel than the MHEV (mean difference: –0.0712 l, 95% CI: [–0.0737, –0.0686]), but more than the split-axle hybrid (mean difference: 0.0398 l, 95% CI: [0.0372, 0.0423]). The split-axle hybrid positioned itself between the MHEV (mean difference: –0.0314 l, 95% CI: [–0.0340, –0.0289]) and the mixed hybrid, indicating intermediate fuel efficiency. These results confirm that PHEV are the most fuel-efficient HEV type.

Figure 9 displays the Monte Carlo simulation results for CO_2 emissions, showing their distributions, mean values, and 95% confidence intervals across various vehicle types and route combinations.

Analysis of CO_2 emissions revealed a significant impact of both hybrid vehicle type and route, as well as their interaction, on emission levels ($p < 0.001$ for all effects and assumed significance levels of σ). At a significance level of $\sigma = 0.05$, the ANOVA test showed a highly significant effect of HEV type ($F = 629{,}708$), route effect ($F = 212{,}121$), and a significant interaction between these factors ($F = 49{,}068$). Similar, highly significant effects ($p < 0.001$ for all) were also observed at significance levels of $\sigma = 0.1$ (F for HEV type = 155,357, F for route = 52,430, F for interaction = 12,137) and $\sigma = 0.2$ (F for HEV type = 38,784, F for route = 13,056, F for interaction = 3029).

In summary, the ANOVA results consistently indicate a statistically significant influence of hybrid vehicle type, route characteristics, and their interaction on CO_2 emission levels, regardless of the assumed significance level ($\alpha = 0.05, 0.1, 0.2$). The results of Tukey's post-hoc test for differences in CO_2 emission values (kg) between hybrid vehicle types are presented in Table 6.

Table 6. Tukey's post-hoc test results for CO_2 emissions differences [kg] among hybrid vehicle types

Parameter	Mean difference	Lower CI	Upper CI	p-value
mixed – MHEV	–0.166	–0.172	–0.160	< 0.001
PHEV – MHEV	–0.725	–0.731	–0.719	< 0.001
split-axle hybrid – MHEV	–0.073	–0.079	–0.067	< 0.001
PHEV – mixed	–0.559	–0.565	–0.553	< 0.001
split-axle hybrid – mixed	0.093	0.087	0.099	< 0.001
split-axle hybrid – PHEV	0.652	0.646	0.658	< 0.001

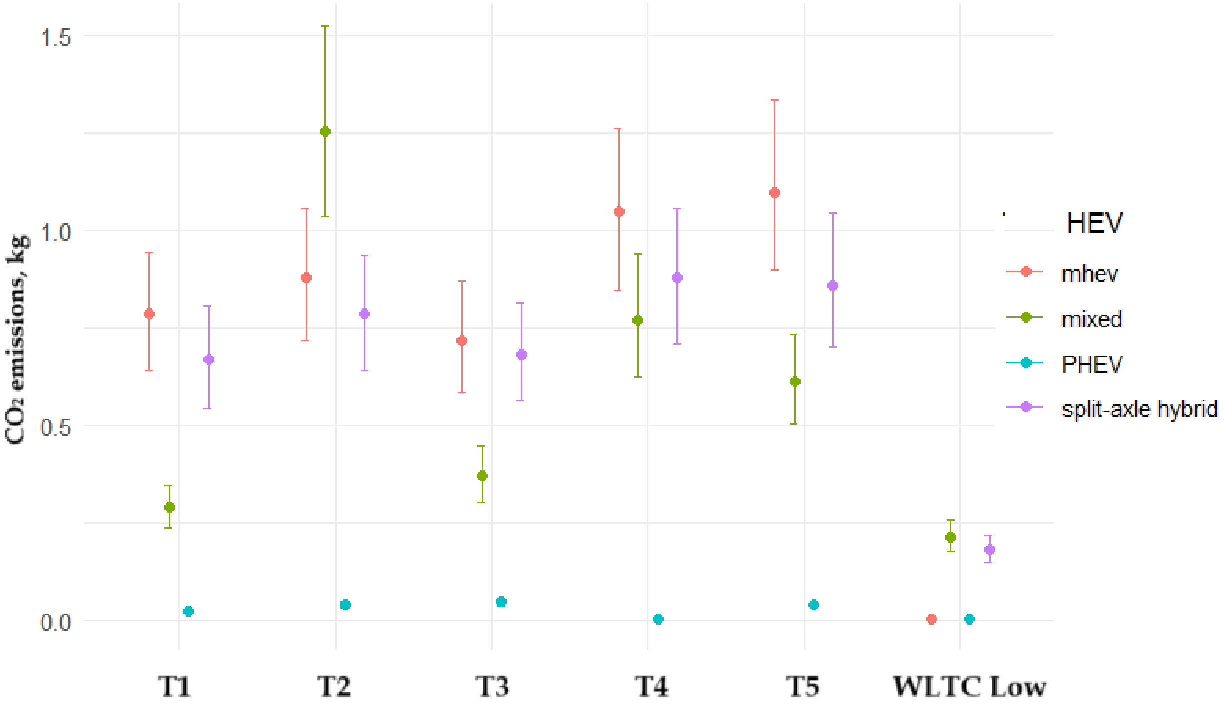

Fig. 9. Distributions of CO_2 emissions [kg] with 95% confidence intervals for $\sigma = 0.1$

Tukey's post-hoc test for CO_2 emissions (kg) revealed statistically significant differences between all pairs of HEV types (p = 0). The largest difference was observed between PHEV and MHEV (mean difference: –0.7252 kg, 95% CI: [–0.7313, –0.7191]), indicating that PHEV emits significantly less CO_2 than MHEV. PHEV also demonstrated lower emissions compared to mixed hybrid (mean difference: –0.5591 kg, 95% CI: [–0.5652, –0.5530]) and split-axle hybrid (mean difference: 0.6520 kg, 95% CI: [0.6459, 0.6581]), achieving the lowest emission values among all types. The mixed hybrid emitted less CO_2 than the MHEV (mean difference: –0.1661 kg, 95% CI: [–0.1722, –0.1600]), but more than the split-axle hybrid (mean difference: 0.0929 kg, 95% CI: [0.0868, 0.0990]). The split-axle hybrid was positioned between the MHEV (mean difference: –0.0732 kg, 95% CI: [–0.0793, –0.0671]) and the mixed hybrid, indicating an intermediate emission level. These results underscore the superior environmental efficiency of PHEVs compared to other HEV types.

The results indicate that both the hybrid vehicle type and the test route exert a crucial influence on fuel consumption and CO_2 emissions. Furthermore, the interaction between these factors suggests that the efficiency of specific HEV types can be optimized depending on driving conditions.

4. Discussion

The findings presented in this study significantly contribute to understanding the impact of traffic congestion on fuel consumption and CO_2 emissions in hybrid electric vehicles operating in urban environments. The simulation analysis, performed using AVL Cruise M software with real-world speed profiles from five urban routes (T1–T5) and the standardized WLTC Low cycle, provided detailed data on the efficiency of four HEV types: plug-in hybrid electric vehicle (PHEV), series-parallel (mixed) configuration, mild hybrid electric vehicle (MHEV), and split-axle hybrid. The application of the Monte Carlo method enabled the estimation of result variability, enhancing the reliability of the analysis despite limited empirical data.

This study distinguishes itself from previous work by its comprehensive approach, analysing four distinct hybrid powertrain configurations under conditions of high traffic congestion. Earlier studies often focused on a single hybrid type or standardized test cycles, leaving a gap in understanding HEV efficiency in diverse, real-world urban conditions. This research fills that gap by offering a thorough comparison, making its findings more representative of actual transportation challenges.

The study revealed that fuel consumption and emission levels are dependent on the hybrid powertrain configuration. Analysis of the driving and idle phases uncovered critical areas for optimizing hybrid powertrain control strategies, particularly during heavy traffic. For example, on route T2, where idle time accounted for 42% of the duration, the mixed hybrid consumed 0.52 l of fuel, whereas the PHEV consumed only 0.02 l. Consequently, under conditions of frequent stops and starts, series-parallel (mixed) and split-axle hybrids are characterized by continuous internal combustion engine operation, leading to increased fuel consumption and higher CO_2 emissions. The data indicate that MHEVs may exhibit lower efficiency in high-density traffic areas, as evidenced by the higher fuel consumption and emissions observed during acceleration cycles and idle phases.

A comparison of fuel consumption and CO_2 emission values from urban routes and the WLTC Low cycle highlights the limitations of current testing standards in reflecting real-world driving conditions. In the WLTC Low cycle, the PHEV exhibited zero fuel consumption, a result of its capability for all-electric operation, facilitated by a large battery energy capacity and an initial battery SOC of 80%. However, on routes T2 and T4, fuel consumption and emissions were significantly higher for all HEV types except the PHEV. It can therefore be concluded that current test cycles do not fully capture the challenges associated with congestion, potentially leading to underestimated fuel consumption and emission values in official vehicle specifications.

Despite certain limitations, such as the absence of empirical tests and the omission of environmental and operational variables (e.g., driving style or temperature) in the AVL Cruise M simulations, as well as the non-inclusion of temperature effects on battery efficiency and fuel consumption, this study possesses significant strengths.

The use of real-world velocity profiles considerably enhances the representativeness of the results for urban conditions, thereby increasing their practical value. Additionally, the application of the advanced Monte Carlo method to estimate result variability constitutes a rigorous approach that effectively compensates for the lack of empirical data, providing a solid foundation for the conclusions. Consequently, despite the mentioned limitations, this study makes a valuable contribution to understanding the impact of congestion on hybrid vehicle efficiency and establishes a robust basis for further research.

5. Conclusions

This research provides crucial insights into the impact of varying urban traffic congestion on fuel consumption and CO_2 emissions in hybrid electric vehicles. It leveraged simulations within the AVL Cruise M environment, utilizing real-world speed profiles (T1–T5) and the standardized WLTC Low cycle. The application of the Monte Carlo method enabled a reliable assessment of result variability across four distinct HEV types.

The analysis revealed that PHEV exhibited minimal fuel consumption and CO_2 emissions, especially in scenarios with frequent stops. This is directly linked to their ability to operate extensively in electric mode, made possible by its high-capacity batteries. Conversely, MHEV demonstrated the lowest efficiency in high-traffic conditions, primarily because its electric drive serves only a supporting role. The split-axle configuration showed better efficiency in smooth traffic flow, underscoring the influence of the hybrid powertrain type on fuel consumption and CO_2 emissions depending on operational conditions. Therefore, the degree of electrification/hybridization is a crucial determinant of the energy and environmental efficiency of hybrid vehicles in urban environments, particularly concerning traffic congestion. A higher degree of electrification, as seen in PHEVs, enables a significant reduction in fuel consumption and CO_2 emissions, making such vehicles most suitable for high-traffic conditions where frequent stops and dynamic driving phases are dominant.

The results also highlighted the imperfections of current testing standards (e.g., WLTC Low) in reflecting real-world urban traffic conditions, potentially leading to an underestimation of actual fuel consumption and emissions. This suggests a need for optimizing hybrid powertrain control strategies, especially in areas characterized by high traffic congestion. It is also worth noting the importance of promoting advanced hybrid technologies, such as PHEVs, within transportation policies.

In summary, the study provides crucial quantitative data that can support the design of more efficient hybrid vehicles and the shaping of urban transportation policies. It emphasizes the pivotal role of real-world road conditions in HEV assessment and indicates the necessity of adapting testing standards to the specifics of urban traffic.

Nomenclature

ANOVA	analysis of variance
CI	confidence interval
CO_2	carbon dioxide
GPS	global positioning system
HC	hydrocarbons
HEV	hybrid electric vehicle
ICE	internal combustion engine
MHEV	mild hybrid electric vehicle
NO_x	nitrogen oxide
PHEV	plug-in hybrid electric vehicle
PM	particulate matter
SOC	state of charge
WLTC	Worldwide Harmonized Light Vehicles Test Cycle

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