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Fuel consumption of diesel, natural gas, hybrid, full electric and hydrogen fuel cells based buses: A simulated comparison using standard road cycles and gradeability tests

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ABSTRACT

Due to the detrimental environmental impact of diesel and gasoline vehicles, alternative propulsion technologies—such as hybrid electric, battery electric, and fuel cell vehicles—have garnered increased attention. However, no studies were found that analyse both gradeability and fuel consumption across varying road inclines for different bus types—diesel, compressed natural gas (CNG), hybrid electric, battery electric, and fuel cell—-while considering the impact of A/C operation. Additionally, limited research has addressed the influence of critical factors, such as bus weight, drag coefficient, and wheel radius, on fuel consumption for these buses. This study addresses this gap by evaluating the fuel consumption and gradeability of five bus types (diesel, CNG, hybrid electric, battery electric, and fuel cell) using the MATLAB/Simulink-based ADVISOR tool.

Fuel consumption was analysed over the Orange County Transit Authority (OCTA) drive cycle under both A/C on and off conditions, and the effects of key vehicle parameters—bus weight, drag coefficient, and wheel radius—were investigated. Fuel consumption was also assessed on the modified Central Business District (CBD-14) drive cycle at 0 %, 2 %, and 4 % road grades. Gradeability tests were conducted at 20 and 40 km/h.

In gasoline equivalent, the battery electric bus exhibited the lowest fuel consumption (29.9 L/100 km with A/C off and 38.4 L/100 km with A/C on), while the CNG bus showed the highest values (87.3 L/100 km with A/C off and 106.9 L/100 km with A/C on). Among the examined parameters, bus weight had the greatest impact on fuel consumption, whereas drag coefficient was the least influential. For a 2 % road grade, the fuel cell bus experienced the largest increase in consumption (78 % with A/C off; 35.5 % for the electric bus with A/C on), while the hybrid electric bus showed the smallest increase. In gradeability tests, the hybrid electric bus achieved the highest climbing capability—22.5 % at 20 km/h and 10.3 % at 40 km/h (A/C off)—compared to the fuel cell bus, which reached only 12.2 % and 7.0 %, respectively; similar trends were observed with A/C on. These findings provide valuable insights into the operational efficiency of different bus technologies under real-world driving conditions.

1. Introduction

The use of fossil fuels in the transportation industry significantly contributes to environmental pollution. While the utilization of hybrid electric, fuel cell, and electric vehicles is gradually increasing in today's world [1], vehicles equipped with internal combustion engines (ICE) are still widely utilized. ICEs offer convenient management and quick refuelling options [2] and the ICE technology has undergone significant advancements. However, its employment with fossil fuels contributes to the exacerbation of environmental pollution. The emission of greenhouse gases leads to global warming. As a result, there is an urgent need to explore alternative propulsion systems that are more environmentally friendly and sustainable.

Diesel engines are recognized for their robustness and fuel efficiency, which contributes to their widespread use in heavy-duty vehicles and

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Nomenclature

Abbreviations	Definition
A/C	Air Conditioning
APU	Auxiliary Power Unit
CBD-14	Central Business District
CNG	Compressed Natural Gas
EB	Electric Bus
EBDCRG	Electric Bus Driving Cycle with Road Gradient Changes
EV	Electric Vehicle
FC	Fuel Consumption
FCB	Fuel Cell Bus
FCV	Fuel Cell Vehicle
GPS	Global Positioning System
GHG	Greenhouse Gas
HEB	Hybrid Electric Bus
HEV	Hybrid Electric Vehicle
HICEV	Hydrogen Internal Combustion Engine Vehicle
ICE	Internal Combustion Engines
MPG	Miles per Gallon
NEDC	New European Drive Cycle
NREL	National Renewable Energy Laboratory
OCTA	Orange County Transit Authority
PEMFC	Proton Exchange Membrane Fuel Cells
SOC	State of Charge
UDDS	Urban Dynamometer Driving Schedule
WLTC	Worldwide Harmonised Light Vehicles Test Cycle
Upper-case roman	Definition
A_v	vehicle front area (m2)
C_D	drag coefficient (−)
F_D	drag force
P_G	power necessary to overcome a road slope
T_o	torque output (Nm)
T_{brk}	the brake torque (Nm)
Lower-case Roman	Definition
f_r	coefficient of the rolling resistance (−)
f_d	total gear ratio (−)
g	gravitational acceleration (m/s2)
m_v	vehicle weight (kg)
r_d	wheel radius (m)
v_v	vehicle speed (m/s)
Greek	Definition
α	angle of the road in rad (°)
η_d	final drive efficiency (−)
ρ	air density (kg/m3)

various industrial applications. Despite these advantages, the environmental impact due to higher emissions of nitrogen oxides and particulate matter remains a critical concern, requiring advancements in emission control technologies [3].

Compressed natural gas (CNG) has numerous advantages over diesel fuel, especially regarding environmental impact and operational expenses. CNG combusts more cleanly than diesel, leading to much lower emissions of nitrogen oxides and particulate matter, both of which significantly contribute to air pollution and respiratory issues. Furthermore, CNG engines emit less carbon dioxide per unit of energy, helping to decrease greenhouse gas emissions. From an economic perspective, CNG is often cheaper than diesel, leading to lower fuel costs for operators [4]. These advantages make CNG a compelling alternative to diesel, particularly in urban regions where maintaining air quality is crucial.

A hybrid electric vehicle (HEV) is designed to store energy in two or more forms on board. In a conventional HEV, one of these forms is gasoline or diesel fuel, which is used in conjunction with an engine acting as a fuel converter. The other form is an electrical storage system. Modern HEVs incorporate advanced technologies to enhance efficiency, such as regenerative braking. This system transforms the kinetic energy of the vehicle into electrical energy for the purpose of recharging the battery, instead of wasting it as heat like conventional brakes. Additionally, some HEVs use their ICE to generate electricity by driving a generator [5]. Moreover, numerous HEVs are equipped with start-stop systems that automatically deactivate the engine when the vehicle is stationary, reducing fuel consumption and emissions. These vehicles often have sophisticated energy management systems that optimize the use of both electric and gasoline or diesel power, resulting in improved fuel efficiency and reduced environmental impact.

Electric vehicles (EVs) operate with electricity stored in batteries, resulting in zero emissions from the exhaust. Consequently, harmful pollutants that contribute to air pollution and climate change, such as carbon dioxide, nitrogen oxides, and particulate matter, are no longer released into the atmosphere. Furthermore, the incorporation of renewable energy sources for charging battery EVs enhances their environmental benefits by reducing reliance on fossil fuels.

Fuel cell vehicles (FCVs) utilize fuel cells as their primary power source. There are various types of fuel cells available. FCVs typically employ proton exchange membrane fuel cells (PEMFCs), where hydrogen is commonly used as the primary fuel, and its chemical energy is converted into electrical energy. FCVs surpass EVs in several aspects. FCVs generally weigh less, occupy less space on the vehicle, and emit fewer GHG. However, EVs also have certain advantages over FCVs. For instance, they entail lower fuel costs per kilometer and provide enhanced accessibility to refuelling infrastructure [6].

Urban transport systems utilize various high-capacity vehicles, with investment costs ranging from lowest to highest for buses, trolleybuses, bus rapid transit, trams, and metros [7]. Approximately 25 % of global final energy consumption is attributed to the transport sector [8]. Buses make up a significant portion of public transportation and diesel buses, as a primary source of vehicle emissions, have had notable adverse effects on human life. The adoption of electricity as a fuel for the transportation sector, in contrast to fossil fuels like petrol, diesel, and natural gas, has significantly contributed to the reduction of global greenhouse gas (GHG) emissions. EVs can reduce GHG emissions by approximately 90 %, HEVs by about 25 %, and plug-in hybrid electric vehicles by 50–80 % [9].

It is evident that varying road conditions (road incline, number of stops, etc.) and distinct bus characteristics (such as the auxiliary power unit in use or vehicle design) significantly impact fuel consumption, highlighting the necessity of considering these factors when selecting buses for passenger transportation [10]. Existing challenges in vehicle optimization include high fuel consumption, component aging, and the need for efficient energy management strategies. Moreover, vehicle performance is highly sensitive to external factors such as road conditions, vehicle load, and driving patterns. The optimization of hybrid and fuel cell vehicles requires balancing energy efficiency, battery durability, and hydrogen consumption, while electric buses face challenges related to battery degradation and charging infrastructure limitations. While recent studies have proposed innovative solutions to address these issues [11–14], the critical role of vehicles in global transportation and urban mobility underscores the need for further advancements. Our study aims to bridge this gap by comprehensively analysing fuel efficiency and gradeability across various bus types under realistic driving conditions, thereby contributing to the global effort of reducing environmental pollution and promoting sustainable urban mobility. The importance of our study can be summarized as follows:

- Comparing the fuel consumption of different buses (diesel bus, CNG bus, hybrid electric bus, electric bus, and fuel cell bus) and observing the impact of air conditioning (A/C) on fuel use.
- Examining the effects of bus weight (which may vary by passenger load or power units), aerodynamic drag coefficient (changes with the vehicle shape), and wheel size on fuel consumption across various buses.
- Analysing fuel consumption of buses over different road inclines, with A/C both enabled and disabled.
- Conducting a gradeability test to assess bus hill-climbing performance.

During our literature review, no studies were identified that simultaneously analyse gradeability performance and fuel consumption across varying road inclines for a range of bus types—including diesel bus, CNG bus, hybrid electric bus (HEB), electric bus (EB), and fuel cell bus (FCB)—while also examining the influence of A/C operation. Additionally, few studies address the effects of critical factors such as bus weight, aerodynamic drag coefficient, and wheel radius on fuel consumption for these bus types [15,16]. This study fills these gaps by offering a comprehensive analysis of both fuel efficiency and gradeability under diverse operating conditions. The key innovations are:

- Comprehensive Evaluation: Simultaneously analysing fuel consumption and gradeability for five bus types under realistic drive cycles.
- Parameter Impact Analysis: Investigating the effects of bus weight, drag coefficient, and wheel radius on fuel consumption
- A/C Operation Impact: Evaluating how A/C operation influences both fuel efficiency and climbing performance.
- Advanced Simulation Techniques: Utilizing the MATLAB/Simulink-based ADVISOR tool to provide robust, quantitative insights.

By adopting this multifaceted approach, the study aims to identify the most fuel-efficient bus types for regions with diverse geographic conditions. The findings will help refine vehicle selection strategies, thereby supporting the development of more sustainable urban transportation systems.

2. Literature review

Numerous research efforts have concentrated on evaluating the performance and fuel efficiency of various vehicle categories through both numerical simulations and experimental methodologies. Such comparative analyses yield valuable information regarding the strengths and weaknesses of different propulsion systems. Durkin et al. conducted a comparative analysis of hydrogen fuel consumption between a FCV and a hydrogen internal combustion engined vehicle (HICEV) using the quasistatic simulation toolbox in Simulink. Their findings indicated that, under the Worldwide Harmonised Light vehicles Test Cycle (WLTC), the FCV demonstrated superior efficiency, consuming only 1.05 kg-H_2 per 100 km, whereas the HICEV exhibited a higher consumption rate of approximately 1.79 kg-H_2 per 100 km [17]. Gautam et al. conducted a comparison between conventional vehicles and HEVs, utilizing the Urban Dynamometer Driving Schedule (UDDS) drive cycle. They demonstrated that HEVs have higher efficiency compared to conventional vehicles. Additionally, they emphasized that HEVs play a crucial role in developing or less developed countries [18]. Dogdu and Reyhancan performed a comparative study on fuel consumption and CO_2 emissions between a vehicle utilizing a series-hybrid drive system and a traditional gasoline-powered vehicle, assessing both the NEDC (New European Drive Cycle) and WLTC cycles. Their findings indicated that integrating an extra-downsized internal combustion engine within the series-hybrid drive system led to a 3.3 % improvement in fuel consumption on NEDC driving cycle compared to the gasoline-powered counterpart [19]. Diaz et al. assessed energy consumption in urban bus networks, focusing on the replacement of ICE buses with EBs. They utilized real global positioning system (GPS) data, terrain models, and a quasi-static longitudinal model to analyse various routes in a city with diverse topography. Their findings demonstrated that transitioning to EBs on an optimized route could reduce energy consumption by 68 % [20]. Keegan et al. employed the ADVISOR software to model four internal combustion engine vehicles, two parallel hybrid electric vehicles, and two series hybrid electric vehicles, each featuring different engine displacements, gearbox types, internal combustion engine power levels, and electric motor power ratings. They conducted a comparative analysis of vehicle performance and fuel consumption across various drive cycles. Their findings revealed that an internal combustion engine vehicle with a 1.9 L engine and an automatic transmission consumed 44 L/100 km, whereas a 1.0 L manual transmission vehicle exhibited a fuel consumption of 30.3 L/100 km under the same drive cycle. Furthermore, their study highlighted the significant fuel-saving potential of hybrid electric vehicles. For instance, a series hybrid electric vehicle equipped with a 1.0 L engine and 200 NiMH battery modules demonstrated a fuel consumption of only 6.65 L/100 km [21].

The ecological consequences associated with various vehicle technologies, especially regarding emissions and energy usage, have been extensively investigated. Some studies examine these impacts across diverse conditions and scenarios. Luu et al. conducted a life cycle impact assessment for electric and conventional buses. The findings suggest that EBs are generally favored across various environmental impact categories throughout their entire life cycle, including GHG emissions, fine particulate matter formation, acidification, and others. They also indicated that the adoption of electric mobility could reduce the carbon footprint by 42.62 gCO_2 per passenger km if conventional buses are replaced by e-buses in Vietnam [22]. Muñoz et al. examined the expenses, fuel usage, and emissions associated with urban buses powered by diesel, natural gas, electricity, and hydrogen. They reported that if the entire fleet in Argentina transitions to FCBs, it could potentially reduce carbon dioxide equivalent emissions by 1.3 Mt, equating to an 87 % decrease in GHG emissions. Alternatively, transitioning to EBs could decrease energy consumption by 25 to 38 % and emissions by 52 to 61 %, resulting in the avoidance of approximately 0.93 Mt of CO_2 equivalent emissions annually [23]. Shahariar et al. investigated the impact of driving style and traffic conditions on emissions and fuel consumption using real-world transient drive cycles with both diesel and a diesel–biodiesel blend. The findings revealed that aggressive driving significantly increased CO_2, NO_x, and CO emissions by up to 37 %, 38 %, and 88 %, respectively. Particulate matter and particle number emissions also rose substantially, by up to 112 % and 538 %. Biodiesel reduced PM and PN emissions by up to 71 % and 68 %, regardless of driving style. Additionally, peak-hour traffic notably increased fuel consumption, underscoring the influence of traffic conditions on efficiency [24].

Developing accurate driving cycles and analyzing real-world driving behaviors are essential for evaluating vehicle performance. Several studies have focused on creating representative driving cycles and understanding how driving patterns influence fuel consumption. Liu et al. developed a method to construct a typical bus driving cycle, incorporating velocity, road slope, and random passenger load. By partitioning kinematic segments between bus stops and synthesizing velocity profiles using the Markov chain Monte Carlo method, the proposed approach demonstrated high accuracy compared to measured cycles. The simulations of fuel consumption for plug-in HEBs highlighted the importance of considering passenger load, resulting in a highly accurate fuel consumption estimation. The relative error was calculated 2.48 %, 1.8 %, and 1.59 % for initial state of charge (SOC) levels of 0.8, 0.6, and 0.4, respectively, making this method highly beneficial for plug-in HEB design and performance evaluation [25]. Ng and Tong compared the driving patterns and energy consumption of electric and diesel buses operating on the same routes in Hong Kong under real-world conditions. The study revealed notable variations in driving behaviors between the two bus types by examining essential driving parameters, speed-acceleration probability distributions, and vehicle-specific power distributions [26]. Nguyen et al. investigated how real-world driving behaviors affect the fuel efficiency of motorcycles, aiming to encourage more sustainable driving practices. Using a data logger to capture instantaneous speed and fuel consumption rates, the analysis identified vehicle-specific power as a key parameter influencing fuel consumption, with a strong correlation (R2 = 0.88). Among the various operating modes of motorcycles, the acceleration mode demands the greatest fuel injection rate into the engine's combustion chamber, approximately 159.9 mg/s, resulting in a fuel consumption of around 3.6 L/100 km. In contrast, the creeping mode is the least fuel-efficient, consuming fuel at a rate 3.2 times greater than that of the cruising mode, with a maximum consumption of up to 7.9 L/100 km [27]. Tong and Ng introduced The Electric Bus Driving Cycle with Road Gradient Changes (EBDCRG). Data on actual bus speed and location were collected during regular operations to analyse distinct driving characteristics. They stated that the developed EBDCRGs, which incorporate road gradient information, provide a realistic representation of the driving environment. The developed EBDCRGs aligned with urban driving cycles for Hong Kong's entire bus network. Comparisons with the Hong Kong supercapacitor bus driving cycle revealed differences in driving characteristics between EBs and supercapacitor buses, with the former showing reduced responsiveness to acceleration [28]. Szilassy and Földes analysed a case study in Budapest with 58 bus lines and 30 buses. The main conclusion of the study was that it is essential to pair buses with differing vehicle specifications to routes that possess unique characteristics. Significant considerations for vehicle selection encompass engine power, fuel consumption, battery and passenger capacity, and weight of the vehicle. Furthermore, route-specific factors like roadway gradient and the frequency of stops critically influence the selection process [10].

The influence of road gradient on vehicle emissions, fuel efficiency, and gradeability performance of the vehicles has been extensively examined in various research studies. These investigations underscore the difficulties that sloped roadways present to vehicle operational efficiency and overall performance. De Almeida and Kruczan investigated the impact of hybridization ratio on vehicle performance and fuel consumption for the Toyota Mirai fuel cell vehicle using the ADVISOR software. Their findings indicated that as the hybridization ratio increased, the maximum gradeability decreased. Specifically, when the hybridization ratio was 18.7 %, the maximum gradeability was 12.9 %, whereas an increase in the ratio to 70.0 % resulted in a decline in gradeability to 6.6 %. However, a rise in the hybridization ratio from 18.7 % to 70.0 % also led to an improvement in acceleration performance, reducing the 0–96.6 km/h acceleration time from 12.4 s to 7.6 s [29]. Jiang et al. investigated the impact of road gradients, varying between −5% and + 5 % in 1 % increments, on the fuel consumption of a diesel vehicle. Their findings indicated that the most significant increase in fuel consumption occurred when the gradient changed from + 3 % to + 4 %. Additionally, at a road gradient of + 4 %, a vehicle traveling at 80 km/h exhibited fuel consumption levels 1.4 and 1.52 times higher than those of the same vehicle traveling at 60 km/h and 40 km/h, respectively [30]. Posada-Henao et al. developed a fuel consumption model for a diesel truck under varying road inclines. Their findings indicate that a fully loaded truck (52 tons) consumes significantly more fuel compared to an empty vehicle (19 tons) under different road gradients. Specifically, fuel consumption was observed to be 2.92 times higher at a 7 % incline, 2.73 times higher at a 5 % incline, and 2.29 times higher at a 2 % incline [31].

The reviewed articles, summarized in Table 1, collectively illustrate the advancements and comparative analyses of various vehicle types. The studies highlight critical findings regarding fuel efficiency, emissions, and operational costs across different driving conditions and technologies.

These studies typically do not address gradeability testing or fuel consumption across varying road inclines for different vehicle types, nor do they consider critical parameters such as bus weight, aerodynamic drag coefficient, wheel radius, or A/C status. This study aims to address these gaps by bridging the findings of prior research, providing a comprehensive analysis of both gradeability and fuel efficiency across diverse bus configurations and road inclines.

Table 1
Summary of the reviewed studies.

Ref.	Year	Investigated Vehicle Type	Key Findings
[17]	2024	FCV and HICEV	Fuel consumption of FCV and HICEV were found as 1.05 kg-H_2 and 1.79 kg-H_2 per 100 km, respectively.
[18]	2021	HEV and Conventional Vehicle	HEVs were shown to have higher efficiency than conventional vehicles
[19]	2024	Gasoline Powered Vehicle and HEV	The integration of an extra-downsized internal combustion engine in the series-hybrid drive system enhanced fuel efficiency by 3.3 % compared to the gasoline-powered vehicle.
[20]	2024	EB	An optimized transition to EBs could lead to a 68 % reduction in energy consumption
[21]	2024	ICE vehicle, parallel HEV, and series HEV	Significant fuel savings can be achieved using hybrid electric vehicles.
[22]	2022	EB and Diesel Bus	EBs were favored in various environmental impact categories throughout their life cycle.
[23]	2022	Diesel Bus, CNG bus, EB and FCB	FCBs could reduce GHG emissions by 87 %, while EBs could lower energy consumption by 25–38 % and emissions by 52–61 %.
[24]	2022	Diesel Bus and Biodiesel Bus	Aggressive driving increased CO_2, NOx, and CO emissions significantly
[25]	2020	Plug-in HEB	A method to construct typical bus driving cycles showed high accuracy in simulating fuel consumption.
[26]	2024	EB and Diesel Bus	Significant differences in driving patterns and energy consumption were observed between EBs and diesel buses.
[27]	2023	Motorcycle	Vehicle-specific power was found to significantly influence motorcycle fuel consumption. The acceleration mode demands the highest fuel injection rate, while the creeping mode is the most fuel-inefficient
[28]	2023	EB and Supercapacitor Buses	The EBDCRG provided a realistic representation of driving conditions and revealed differences in driving characteristics between EBs and supercapacitor buses.
[10]	2024	EB	The study emphasized the importance of pairing buses with appropriate vehicle specifications to routes with unique characteristics, considering factors like fuel consumption and roadway gradient.
[29]	2021	FCV	Raising the hybridization ratio improved acceleration performance, but reduced gradeability performance.
[30]	2025	Diesel Vehicle	Fuel consumption increased significantly from + 3 % to + 4 % road gradient, with consumption at + 4 % being 1.4 and 1.52 times higher at 80 km/h compared to 60 km/h and 40 km/h, respectively.
[31]	2023	Diesel Vehicle	A fully loaded diesel truck (52 tons) consumes significantly more fuel than an empty truck (19 tons) on various inclines, with consumption 2.92, 2.73, and 2.29 times higher at 7 %, 5 %, and 2 % inclines, respectively

3. Material and methods

The study's methodology, including validation of the ADVISOR model, creating different bus models, scenario simulation and analysis, is summarized in Fig. 1 to provide a structured overview of the key steps undertaken.

3.1. Fundamental concepts in vehicle performance

Inertia is the tendency of an object to resist any change in its state of motion, whether that change involves speed, direction, or stopping [32]. The vehicle inertia can be calculated in the following equation:

$$m_v v_v = \left[\frac{(T_o f_d + T_{brk})\eta_d}{r_d}\right] - \left(\frac{1}{2}\rho C_D A_v {v_v}^2\right) - [m_v g(f_r cos\alpha + sin\alpha)] \quad (1)$$

In this formula, m_v is the vehicle weight (kg), v_v is the vehicle speed (m/s), T_o shows the torque output from the powertrain (Nm), f_d total gear ratio (−),T_{brk} is the brake torque (Nm), η_d is the final drive efficiency (−), r_d indicates the wheel radius (m), ρ is the air density (kg/m^3), A_v shows the vehicle front area (m^2), g indicates the gravitational acceleration (m/s^2), f_r is the coefficient of the rolling resistance (−), α is the angle of the road in rad (°) and C_D is the drag coefficient (−) [33–35].

Gradeability refers to the steepest incline on which a vehicle can maintain a specified constant speed. It characterizes the vehicle's ability and capacity to overcome slopes [36]. Gradeability is represented as a percentage, corresponding to the tangent of the road's incline angle [37]. The road grade affects the inertia (see Equation (1) and thus, the fuel performance since the vehicle requires additional power to overcome both gravitational and frictional resistances as the incline increases. This demand is especially significant at higher slopes, where the force of gravity, represented by "*mgsinα*" adds to the resistance encountered by the vehicle. Additionally, rolling resistance "$mgf_r cos\alpha$", also increases as the load on the tires grows with the incline. Both forces act against the vehicle's forward motion, requiring the engine to produce more torque to maintain the same speed. Consequently, this leads to higher fuel consumption and reduced efficiency. Neglecting to account for road grade in the analysis of vehicle fuel consumption and performance can result in considerable inaccuracies. Furthermore, such miscalculations indirectly affect the accuracy of emissions predictions, as higher fuel consumption typically correlates with increased pollutant emissions, making it critical to include road grade in comprehensive vehicle evaluations. The power necessary to overcome a road slope (P_G) while ascending a hill is calculated with the following equation [38]:

$$P_G = \frac{1}{2}\rho C_D A_v {v_v}^3 + m_v g v_v sin\alpha + m_v g f_r v_v cos\alpha \quad (2)$$

Fuel economy represents how efficiently a vehicle converts fuel energy into distance travelled, usually measured as fuel consumption (liters per 100 km, or L/100 km) or fuel efficiency (miles per gallon, or MPG) [39]. Lower fuel consumption or higher MPG indicates better efficiency, meaning the vehicle uses less fuel to cover a given distance. MPG can be calculated with the following equation [36];

$$MPG = \frac{Totaldrivenmiles * Energyofonegallongasoline}{Totalfuellsenergyconsumed} \quad (3)$$

In this study, fuel consumption is compared using gasoline-equivalent units to provide a standardized method for assessing the energy use of various bus technologies. Since buses can operate on different energy sources, comparing fuel consumption directly in terms of their respective energy sources would make cross-technology

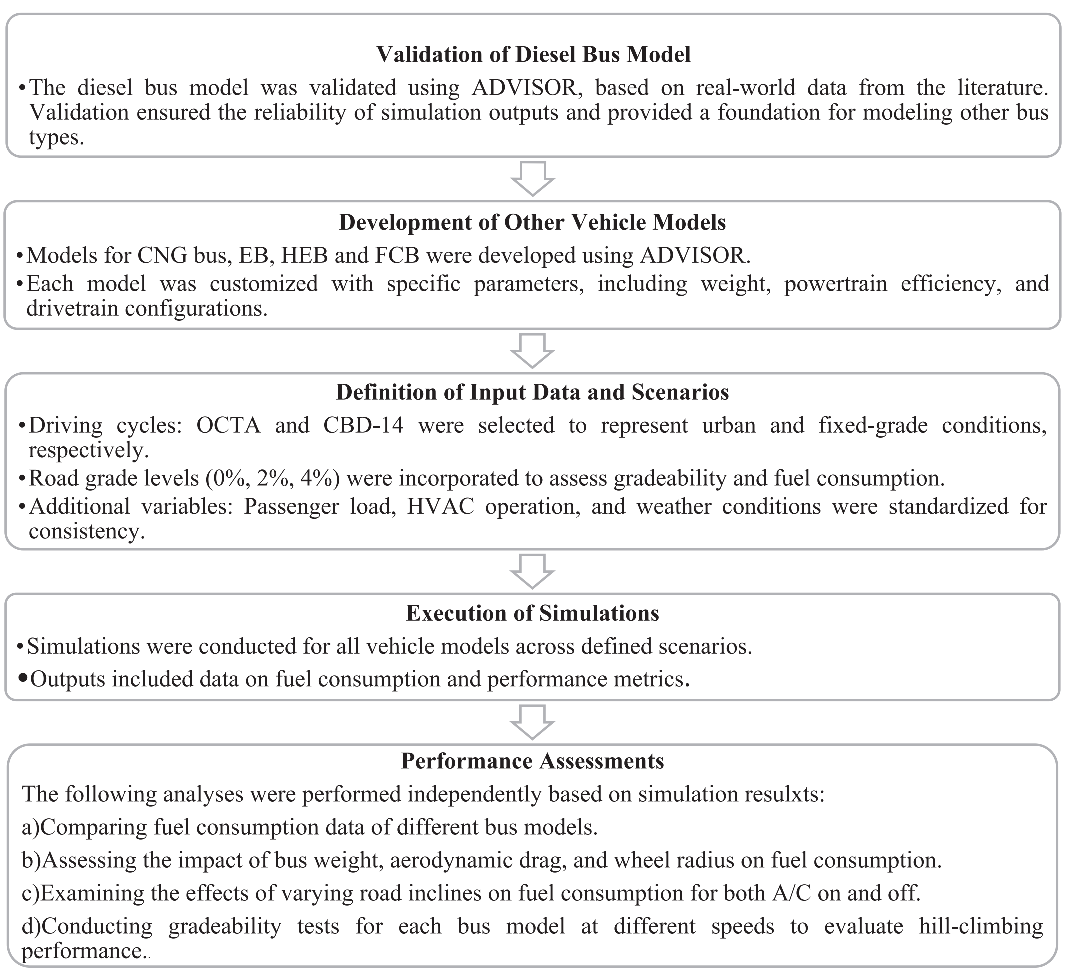

Fig. 1. Methodological Framework of the Study.

comparisons difficult. By converting all fuel types into gasoline equivalents, we establish a common reference point based on the energy content of gasoline, which simplifies comparisons and highlights the relative efficiency of each technology. Same method has been utilized by other authors [40–42]. The conversion to gasoline equivalents is based on the energy content of the fuel or electricity used by the vehicle, compared to the energy content of gasoline. For example, one gallon (3.785 L) of gasoline has an energy content of 33.7 kW-hr, which corresponds to the energy provided by consuming 1 kg of hydrogen [40]. The formulation for converting fuel consumption into gasoline equivalent is [43]:

$$GasolineEquivalent = \frac{FC}{EC_F} * EC_G \tag{4}$$

Here, FC represents the fuel consumption of the vehicle, EC_F is the energy content of the specific fuel type employed and EC_G signifies the energy content of gasoline.

The relationship between a vehicles structure and the surrounding air plays a crucial role in determining the aerodynamic forces exerted on the vehicle, which in turn can have a substantial effect on fuel efficiency and overall operational performance. A comprehensive understanding of these aerodynamic concepts is vital for enhancing bus design, as streamlined airflow minimizes drag and enhances stability. By focusing on aerodynamic efficiency, manufacturers can create vehicles that are more energy-efficient, thereby meeting the demands of modern transportation. Optimizing vehicle design to minimize drag involves meticulous shaping of the vehicle's body and the integration of diverse aerodynamic features. This approach is essential for improving both efficiency and performance. The following equation can be used for calculating the drag coefficient [44]:

$$C_D = \frac{2F_D}{\rho A_v {v_v}^2} \tag{5}$$

In this equation, F_D is the drag force.

3.2. Drive cycle

Drive cycles represent sequences of vehicle speeds over a specific trip duration and are commonly employed to evaluate vehicle performance [45]. These cycles replicate real-world driving conditions, facilitating uniform evaluations of fuel efficiency, emissions, and the comprehensive dynamics of vehicles. This study employs two distinct drive cycles to simulate various bus performance characteristics: the CBD-14 and the OCTA drive cycles. Although some studies report similar outcomes in fuel economy and emissions for both the CBD-14 and OCTA drive cycles [46,47], others suggest that the CBD-14 drive cycle lacks sufficient realism to accurately represent actual bus operations and may be considered hypothetical [46,48]. Thus, fuel economy calculations and analyses of the impacts of bus weight, aerodynamic drag, and wheel radius on fuel consumption were performed using the OCTA drive cycle. For evaluations at fixed road grades, the CBD-14 drive cycle was adapted to align with these conditions, as the higher-speed segments in the OCTA drive cycle can lead to considerable discrepancies between target and actual speeds during simulations on inclined roads, reducing its reliability for fixed-grade assessments [49].

The CBD-14 drive cycle consists of 14 identical segments, each involving acceleration to roughly 32.18 km/h, maintaining that speed, deceleration to a complete stop, and a stationary dwell period. The full cycle spans 3.23 km and takes a total of 570 s to complete. This sequence provides a standardized pattern for evaluating vehicle performance across acceleration, steady speed, and braking phases. CBD-14 drive cycle is commonly used to evaluate transit buses [50].

The OCTA drive cycle, developed by West Virginia University, is a chassis dynamometer test tailored for heavy-duty vehicles, encompassing segments that emulate both urban and highway driving conditions. Considering the usual driving behaviours of urban transit buses in Los Angeles, California, this drive cycle spans a total distance of 10.53 km, with a duration of 1909 s. The OCTA drive cycle is also frequently used for analysing buses [51,52]. The velocity profile of the CBD-14 drive cycle is presented in Fig. 2, while Fig. 3 displays the OCTA drive cycle.

3.3. Introduction to ADVISOR and development of the diesel bus model

The Advanced Vehicle Simulator, commonly referred to as ADVISOR, was developed by the National Renewable Energy Laboratory (NREL). This versatile tool predicts the performance of various vehicle types, including conventional, hybrid electric, electric, and fuel cell vehicles, while considering their performance across different driving cycles [53]. As a MATLAB/Simulink tool, ADVISOR provides a user-friendly graphical interface that allows for detailed vehicle configuration. Being open-source and operating offline, it is well-suited for modelling and simulation tasks, leveraging modules from MATLAB/Simulink. The integration of the MATLAB/Simulink interface in ADVISOR enhances its flexibility in vehicle modelling and control strategy development, allowing users to easily modify algorithms such as braking systems for more tailored simulations. Users can choose from nine predefined driving systems, with configurations that include selections from 19 electric motors, nine types of batteries, and seven fuel cells [41]. This capability facilitates comprehensive analysis of different vehicle configurations and presents system performance results in a clear graphical format, which is critical for optimizing vehicle designs and improving operational efficiency. Moreover, ADVISOR has gained significant traction among automobile manufacturers and researchers in both academic and industrial sectors. The software benefits from a robust community of users who have contributed new components and data, thereby enriching the ADVISOR library [41,53,54]. On the other hand, although highly beneficial in providing real-world data, field testing often requires significant resources, including specialized equipment, facilities, and extensive time allocation.

In this study, ADVISOR was selected to conduct performance analyses of buses utilizing different fuel types, as its compatibility with NREL's real-world data allowed for accurate and efficient simulations, effectively substituting for physical testing. Initially, the Orion VI low-floor transit bus with a 205 kW diesel engine was modelled using ADVISOR. The modelled bus has a fraction of vehicle weight on the front axle when stationary of 0.45, a wheelbase of 6.86 m, a glider mass of 12636 kg, a frontal area of 6.52 m2, and a vehicle drag coefficient (C_D) of 0.79 [55]. It is certainly possible to model other buses using the ADVISOR software. However, the ORION VI model was selected because the vehicle specifications were already defined in the ADVISOR software, and real fuel consumption data [56] for this model is readily available. The MATLAB/Simulink block diagram of the created bus model for the diesel engine is shown in Fig. 4.

3.4. Validation of diesel bus fuel consumption

NREL reports that the fuel consumption of the ORION VI diesel bus is 3.2 MPG diesel equivalent with the A/C on and 4.0 MPG diesel equivalent with the A/C off. The A/C off fuel consumption was determined using chassis dynamometer data over the CBD-14 drive cycle, while the A/C on fuel consumption was estimated by incorporating the best approximation of A/C load into the model based on A/C off conditions, followed by simulations using the ADVISOR tool. The estimation of fuel consumption with A/C on was established through consensus within the 21CT Program Transit Bus Working Group, with input from both industry and government stakeholders [56].

For this study, validation of the ADVISOR model was achieved by directly comparing real-world fuel consumption data from NREL for the CBD-14 drive cycle [56] with our simulated results for the diesel bus. Over the approximately 3.23 km CBD-14 drive cycle, we calculated a total fuel consumption of 2.437 L of diesel with the A/C on, compared to approximately 2.0 L with the A/C off. Our simulations indicated fuel

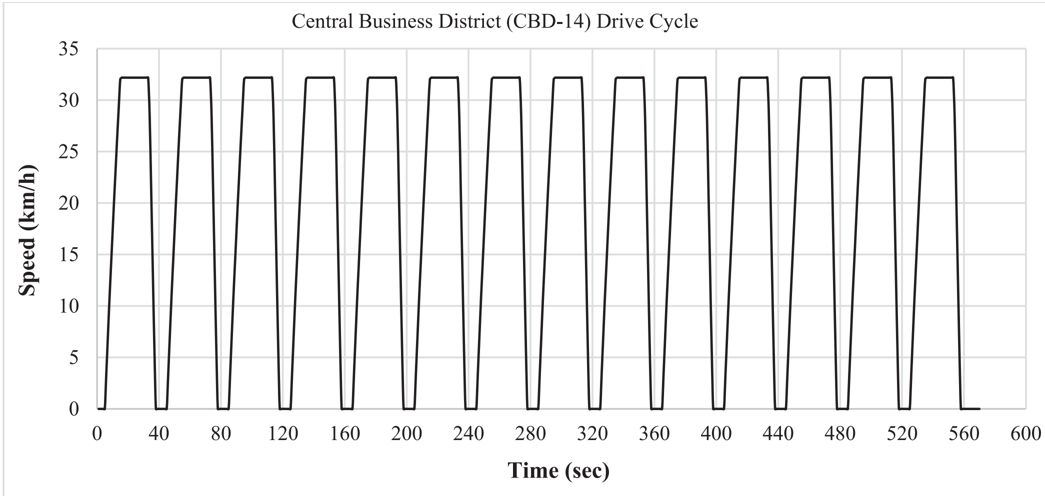

Fig. 2. The Central Business District (CBD-14) drive cycle.

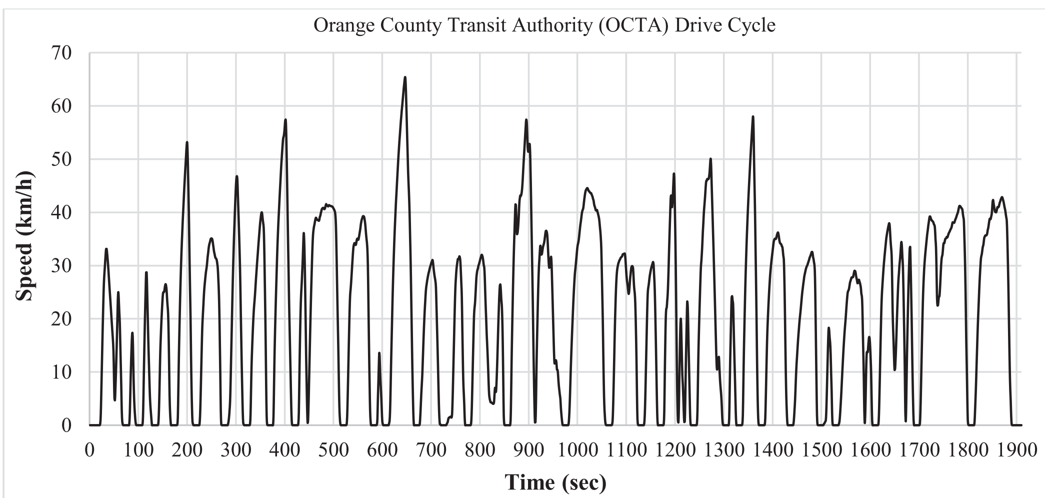

Fig. 3. Orange County Transit Authority (OCTA) drive cycle.

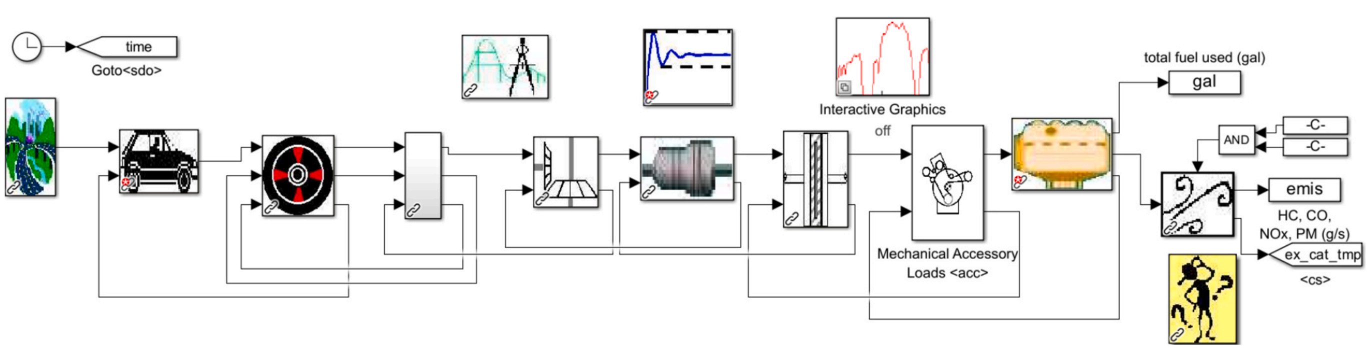

Fig. 4. MATLAB/Simulink block diagram for the diesel engine bus.

consumption values of 61.9 L of diesel per 100 km (3.8 MPG diesel equivalent) with the A/C off, and 75.4 L of diesel per 100 km (3.1 MPG diesel equivalent) with the A/C on, aligning with the real-world data reported by NREL. In these simulations, the A/C load was specified as 14 kW [56]. These findings are instrumental for validating the numerical outcomes of the ORION VI bus model equipped with a diesel engine.

The ADVISOR interface also provides fuel consumption in gasoline equivalent units (see Equation (4). Under these metrics, fuel consumption was calculated at 70.9 L of gasoline per 100 km with the A/C off, and 86.3 L of gasoline per 100 km with the A/C on. As we mentioned before, we decided to compare the fuel consumption of different buses in gasoline equivalent because it allows for direct comparability across various bus types. Table 2 shows both experimental and simulated fuel consumption data.

Table 2
Direct Comparison of Fuel Consumption Data for ORION VI Bus: NREL Reported Values vs. Simulated Results from CBD-14 Drive Cycle.

Condition	NREL [56]	Simulated Data (This Study)	
A/C Off	4.0 MPG	3.8 MPG	70.9 L gasoline equivalent
A/C On	3.2 MPG	3.1 MPG	86.3 L gasoline equivalent

3.5. Modelling different bus types

Following the validation of fuel consumption data, various bus models were developed, primarily to assess their ability to successfully perform the CBD-14 and OCTA drive cycles while maintaining close alignment between actual and target speeds. Despite a skilled driver's efforts to follow a designated speed profile, minor fluctuations are inevitable. To address this limitation, each standardized fuel economy testing protocol establishes specific upper and lower speed limits for each driving cycle [49]. Driving behaviours and patterns significantly affect both fuel efficiency and exhaust emissions. Consequently, some researchers have opted to use robotic drivers in vehicle tests to minimize potential errors [57]. The Environmental Protection Agency (EPA) has recommended that, to minimize errors in measuring vehicle performance, the vehicle speed should deviate from the target speed specified in the drive cycle by no more than ± 3.21 km/h, and such deviations should not exceed a duration of 2 s. However, speeds that fall below the prescribed levels are permissible as long as the vehicle operates at its maximum available power during those instances [58]. In this study, the powertrains of the various bus types modelled were designed in accordance with the EPA's recommendations.

When developing the hybrid electric bus model, the battery module was configured in two different scenarios of 15 and 30 units alongside the diesel engine, and the impact of these configurations on bus performance was analysed.

Fig. 5a illustrates the variation in the SOC of the energy storage system during the OCTA drive cycle for both 15 and 30 battery modules, each rated at 12 V and 60Ah, with the A/C turned on. When 15 modules are used, the battery modules deplete their charge, and the buses diesel engine must meet the desired speeds of the drive cycle. This results in a slight discrepancy between the required speed and the actual bus speed. To resolve this issue, the power of the internal combustion engine can be increased, allowing for fewer battery modules to be used.

Fig. 5b illustrates the battery module temperature when different numbers of modules are employed. Using fewer battery modules imposes a greater load on the batteries, potentially leading to higher battery temperatures. The maximum battery module temperature observed with 15 modules was 59.5 °C, whereas with 30 modules, it was 34.7 °C. Considering that the maximum temperature for a nickel–metal hydride battery system should be around 70 °C, and that higher temperatures would increase the cost and design of the cooling system [59], and the determination of an appropriate number of battery modules are crucial. These factors significantly impact vehicle performance and ensure the battery does not pose a fire hazard, thereby enhancing safety. In the calculations, it was assumed that the SOC of the battery module starts at 0.7, and the initial battery module temperature is 20 °C.

A similar situation observed in the hybrid electric bus was also noted for the electric bus. Fig. 6 illustrates the changes in electric bus speed with 30 and 50 battery modules under A/C on conditions over OCTA drive cycle. With the A/C on, the electric bus was unable to complete the drive cycle using 30 modules of 12 V 60Ah batteries due to depletion of battery SOC before the drive cycle's completion. However, with 50 modules of 12 V 60Ah batteries, the electric bus was able to achieve the required performance, maintaining adequate SOC to complete the drive cycle with minimal deviation from the prescribed speed profile, in alignment with EPA-recommended conditions.

For the diesel and CNG buses, parameters such as the auxiliary power unit (APU) and transmission characteristics were determined based on information available in the literature [56]. In designing hybrid electric, electric, and fuel cell buses, the conditions recommended by the EPA were taken into account, with the aim of minimizing the difference between the instantaneous speed of the buses in the drive cycle and the bus speed at in our simulation at any given moment, t. Table 3 presents data for the CBD-14 and OCTA drive cycles.

In Table 3, *Avg.Diff* indicates the absolute average difference between the target speed (see Figs. 2 and 3) during the drive cycle and the speeds achieved by the bus during simulation, $Diff_t > 3.21_{kph}$ shows the total percent of time with the difference of target speed and the bus speed is higher than 3.21 km/h, and $Diff_{max,t}$ indicates highest absolute difference between the target and the bus speed in km/h.

An important consideration was ensuring that the bus configuration accounted for the A/C being on. This scenario was chosen because it imposes a higher power demand on the engine, making it more challenging for the bus to follow the drive cycle. Consequently, by contemplating the worst-case scenario, components such as the APU, electric motor, fuel cell size, and the number of battery modules were defined. Table 4 presents the five different bus models that were created. The variation in weight among the buses is due to the differences in components such as the engines and batteries used in each model. It should be noted that the simulations were conducted under the assumption that the bus is loaded with 26 passengers, based on a standard weight assumption of 68 kg per person [56].

The hybrid electric bus is outfitted with a 171 kW diesel engine, augmented by an integrated battery system. The electric bus operates independently of any internal combustion engine, relying exclusively on battery technology as its singular energy source. The fuel cell bus was equipped with four ANL Model – 50 kW (net) ambient pressure hydrogen fuel cell systems, providing a combined maximum power

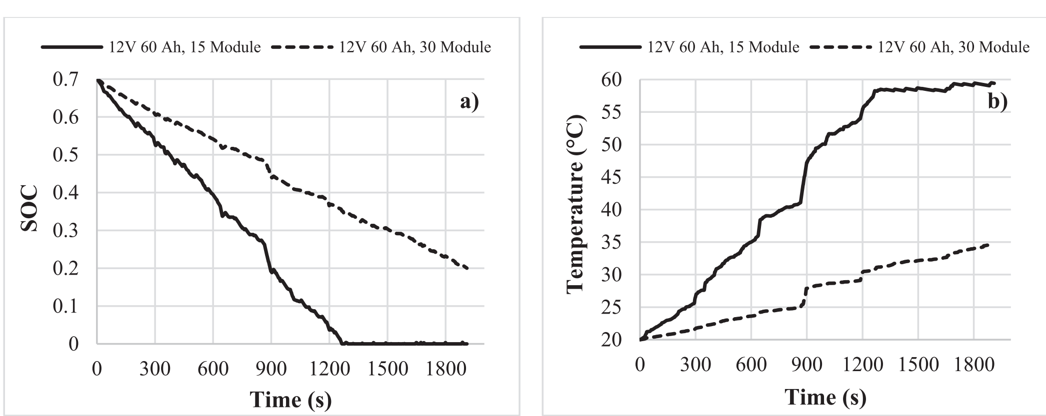

Fig. 5. A) battery modulestate of charge (SOC) and b) temperature (°C) for the hybrid electric bus.

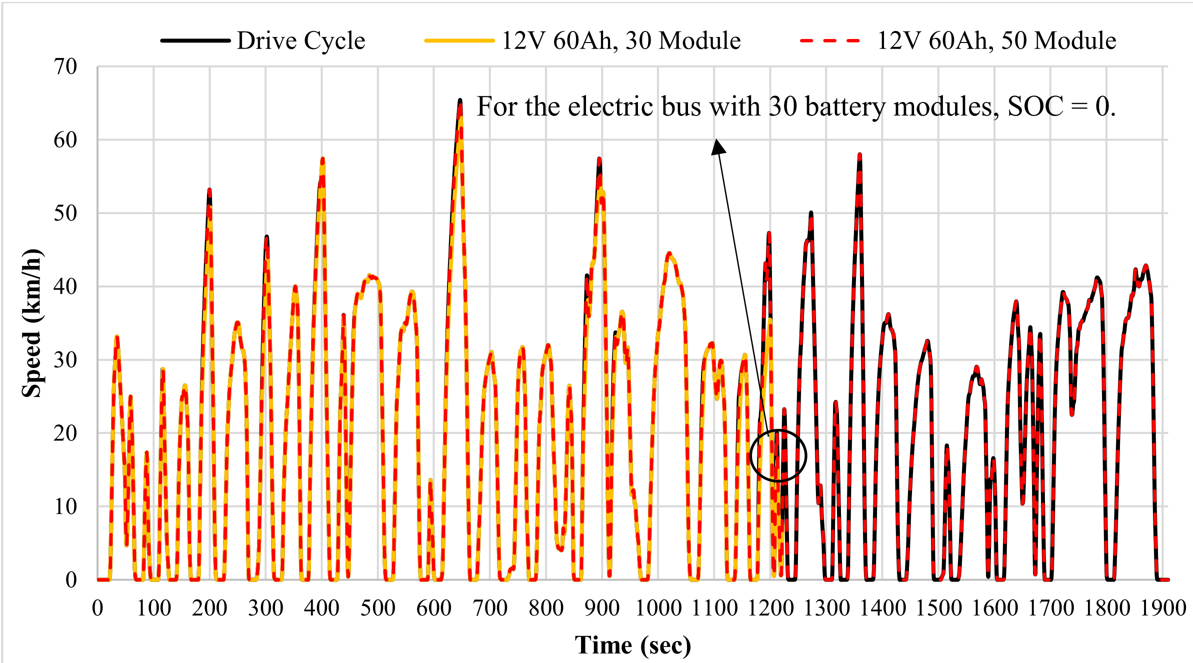

Fig. 6. Actual vs. required speed for the electric bus with varying number of battery modules during A/C on in the OCTA drive cycle.

Table 3
Comparison of Speed Deviations for Different Bus Types.

Drive Cycle	Vehicle	$Avg.Diff(km/h)$	$Diff_t > 3.21_{km/h}$	$Diff_{max,t}(km/h)$
OCTA	Diesel Bus	0.115	1.52 %	8.38
	CNG Bus	0.4	5.02 %	12.05
	Hybrid Electric Bus	0.0007	0 %	0.518
	Electric Bus	0.003	0 %	0.69
	Fuel Cell Bus	0.1755	1.52 %	6.52
CBD-14	Diesel Bus	0.044	0 %	0.00315
	CNG Bus	0.021	0 %	0.48
	Hybrid Electric Bus	0.0246	0 %	0.00155
	Electric Bus	0	0 %	0
	Fuel Cell Bus	0.01	0 %	0.31

output of 200 kW. Similar fuel cell models have been frequently employed in the literature for modelling fuel cell vehicles [41,42,60,61]. The efficiency curves of the APU's and electric motors used in this study is shown in Fig. 7.

4. Results

In this study, five different bus models were designed: a diesel bus, a CNG bus, a hybrid electric bus, an electric bus, and a fuel cell bus. Fuel consumptions of five different bus models were calculated in terms of gasoline equivalent, both with the A/C off and on. Following this, the impacts of bus weight, aerodynamic drag coefficient, and wheel radius on fuel consumption were determined for each bus type. Subsequently, fuel consumption was computed for various fixed road inclines of 2 % and 4 % under both A/C on and A/C off conditions, after which gradeability tests were performed. All the above analysis were performed using the MATLAB/Simulink based ADVISOR tool.

4.1. Fuel consumption of different bus models

Fuel consumption of different bus models was calculated under both A/C off and A/C on conditions using the OCTA drive cycle and is presented in the Table 5. For better understanding, comparisons were made in terms of gasoline equivalent (see Equation (4)).

Upon examining the table, it is observed that the electric bus had the lowest fuel consumption in both A/C on and A/C off conditions, while the CNG bus had the highest fuel consumption in both scenarios. The fuel consumption per 100 km in gasoline equivalent was 29.9 L for the electric bus with A/C off and 38.4 L with A/C on, whereas for the CNG bus it was 87.3 L with A/C off and 106.9 L with A/C on. When assessing the effect of A/C on fuel consumption, it was found that A/C increased fuel consumption by approximately 23.3 % for diesel bus, 22.5 % for CNG bus, 4.7 % for hybrid electric bus, 28.4 % for electric bus, and 19.2 % for fuel cell bus. Therefore, air conditioning had the most significant impact on fuel consumption in the electric bus and the least impact on the hybrid electric bus.

Table 4
Properties of the created bus models.

Vehicle Type	Diesel Bus [56]	CNG Bus [56]	Hybrid Electric Bus (HEB)	Electric Bus (EB)	Fuel Cell Bus (FCB)
Weight	14515 kg	15223 kg	15797 kg	15,194	15,879
APU	Detroit Diesel Corp. Series 50 8.5 (205 kW) Diesel Engine	John Deere 8.1L (209 kW) CNG SI Engine	Detroit Diesel Corp. Series 30 7.3L (171 kW) Diesel Engine	–	Fuel Cell 200 kW
Electric Motor	–	–	Westinghouse 75-kW (continuous) AC induction motor	187-kW (continuous) 3-phase AC induction motor/inverter	187-kW (continuous) 3-phase AC induction motor/inverter
Battery	–	–	60 Ah NiMH, 12 V, 30 modules	60 Ah NiMH, 12 V, 50 modules	28 Ah NiMH, 6 V, 60 modules

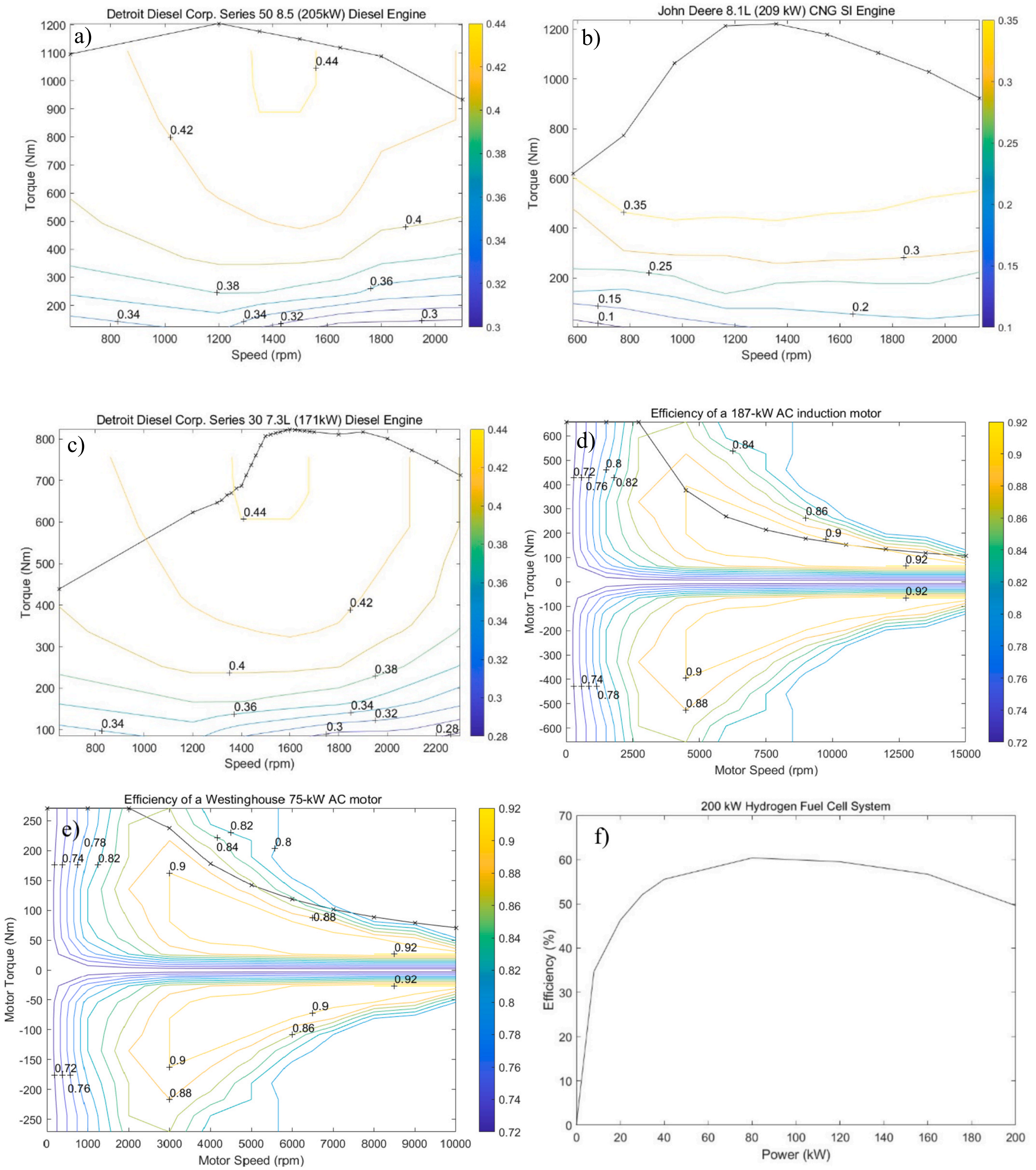

Fig. 7. Efficiency contour diagram vs. torque and speed characteristics of a) 205 kW diesel engine b) 209 kW CNG SI engine c) 171 kW diesel engine d) 187 kW AC induction motor e) Westinghouse 75 kW AC motor f) the efficiency map of the 200 kW fuel cell stack.

4.2. Impact of weight, drag coefficient and wheel radius on fuel consumption

It is evident that the vehicle weight, aerodynamic drag coefficient, and wheel radius influence vehicle inertia and thus fuel consumption (see Equation (1). The impact of these three variables on fuel consumption for different bus types over the OCTA drive cycle is shown in Fig. 8. These calculations were performed with the A/C off, considering that the increased power demand with the A/C on, especially in heavier vehicles, could affect the accuracy of the results. While one parameter was varied, the other was kept constant at a specified baseline value. Fuel consumption data are presented in gasoline equivalent terms

Table 5
Fuel consumption of different bus types for the A/C off and A/C on.

Vehicle Type	Diesel Bus [56]		CNG Bus		Hybrid Electric Bus (HEB)		Electric Bus (EB)		Fuel Cell Bus (FCB)	
	A/C off	A/C on	A/C off	A/C on	A/C off	A/C on	A/C off	A/C on	A/C off	A/C on
Fuel Consumption (L/100 km)	61.9	76.3	273	334.3	48.3	50.5	–	–	785.8	937.3
Fuel Consumption L/100 km (Gasoline equivalent)	70.9	87.4	87.3	106.9	55.3	57.9	29.9	38.4	53.2	63.4

and calculated by using the Equation (4).

To analyse the impact of selected variables on fuel consumption, all values were increased and decreased by 10 %. The weight of the bus varies based on factors such as the type and size of the engine, battery capacity, the materials used in its construction, and the number of passengers on board. Given that the simulations were conducted with the assumption of 26 individuals on board (25 passengers and one driver), and considering that the modelled bus has a capacity of 50 seated passengers, the weight can vary by up to 1,700 kg based solely on the number of occupants, assuming a weight of 68 kg per person [56]. When choosing C_D values, existing studies have been carefully investigated. Particularly in older models of buses with front corners, the C_D can reach values as high as 0.93 [62,63]. However, it is possible to reduce this coefficient through aerodynamic enhancements [64]. Values observed in the literature guided the selection of the analysed wheel radii, ensuring alignment within established ranges [20,65–67]. The newly calculated fuel consumptions, expressed in gasoline equivalents, are shown in Fig. 8 and Table 6, alongside their percentage changes. In the Table 6, F_{cg} represents fuel consumption in gasoline equivalents (liters/100 km), and %d indicates the percentage increase or decrease in fuel consumption for each scenario.

When examining Fig. 8 and Table 6 together, it is observed that bus weight has the most significant impact on fuel consumption, while aerodynamic drag has the least. A reduction in bus weight decreased fuel consumption the most in the CNG bus (7.97 %) and, an increase in weight led to the highest fuel consumption increase in the same bus type (10.79 %). Changes in bus weight had the least impact on the FCB. Reducing the FCB's weight decreased fuel consumption by 4.87 %, while increasing the weight resulted in only a 4.44 % increase in fuel consumption.

The vehicle's aerodynamic design, represented by the C_D value, was tested at three different levels: 0.71, 0.79, and 0.87. The calculations showed that changes in C_D had the most significant effect on the hybrid electric bus. An increase in C_D resulted in a 0.61 % increase in fuel consumption for the hybrid electric bus, while a decrease in C_D reduced fuel consumption by 0.87 %. The effects of C_D changes on diesel bus, CNG bus, and FCB were relatively similar. The smallest reduction in fuel consumption due to a lower C_D was observed in the diesel bus (0.31 %), while the smallest increase in fuel consumption due to a higher C_D was seen in the electric bus (0.33 %).

The wheel radius was also adjusted by ± 10 %, with examinations conducted at radii of 0.45, 0.5, and 0.55 m. Increasing the wheel radius led to the highest increase in fuel consumption (3.25 %) for the CNG bus, while reducing the wheel radius resulted in the greatest decrease in fuel consumption (3.73 %) for the same bus. The smallest increase in fuel consumption due to a larger wheel radius was observed in the diesel bus (0.55 %), while the smallest decrease in fuel consumption due to a smaller wheel radius was noted in the FCB (1.15 %). The results clearly

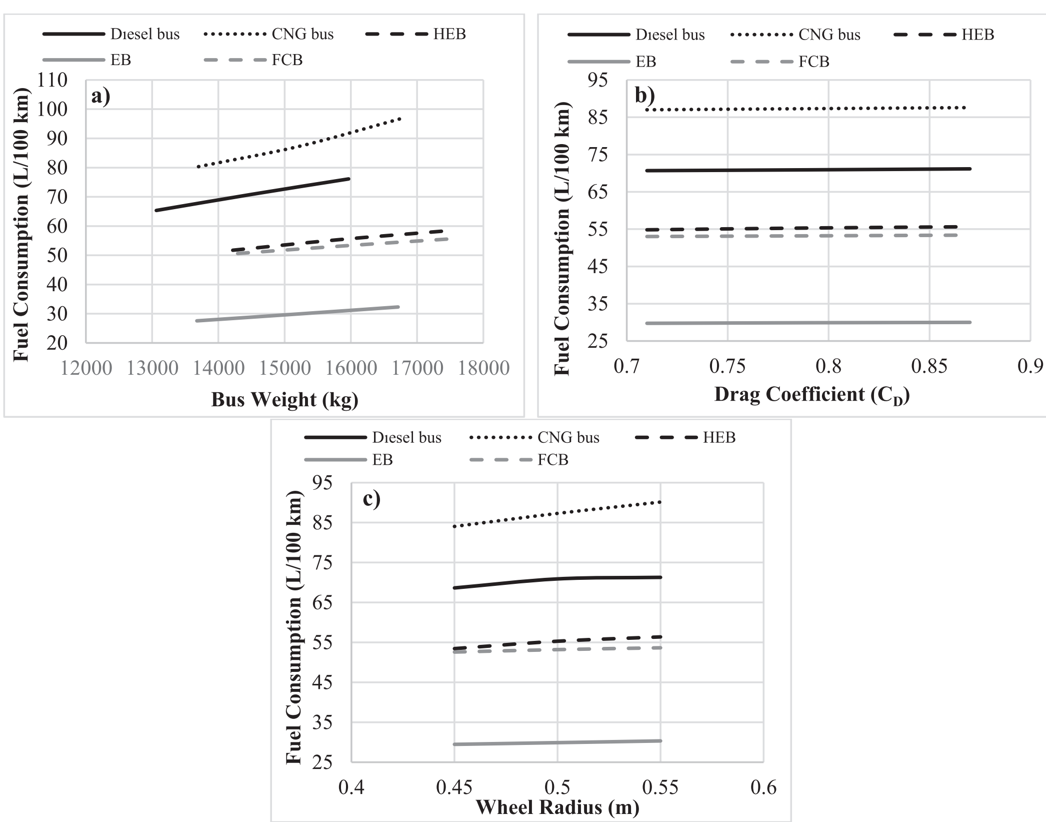

Fig. 8. Effect of a) bus weight ($C_D = 0.79$, $r_d = 0.5$ m) b) drag coefficient ($m_v = 14515$ kg, $r_d = 0.5$ m) c) wheel radius ($m_v = 14515$ kg, $C_D = 0.79$) on the fuel consumption (gasoline equivalent).

Table 6
Effect of bus weight, drag coefficient and wheel radius on fuel consumption for different bus types.

Bus Weight, m_v (kg) ($C_D = 0.79$, $r_d = 0.5$ m)

Diesel Bus			CNG Bus			Hybrid Electric Bus			Electric Bus			Fuel Cell Bus		
m_v	F_{cg}	%d	m_v	F_{cg}	%d	m_v	F_{cg}	%d	m_v	F_{cg}	%d	m_v	F_{cg}	%d
13,063	65.34	7.84	13,700	80.34	7.97	14,217	51.73	6.45	13,675	27.57	7.79	14,291	50.61	4.87
14,515	70.9	–	15,223	87.3	–	15,797	55.3	–	15,194	29.9	–	15,879	53.2	–
15,966	76.13	7.37	16,745	96.7	10.79	17,377	58.24	5.32	16,713	32.3	8.03	17,467	55.56	4.44

Drag coefficient, C_D (–) ($m_v = 14{,}515$ kg, $r_d = 0.5$ m)

–	Diesel Bus		CNG Bus		Hybrid Electric Bus		Electric Bus		Fuel Cell Bus	
C_D	F_{cg}	%d	F_{cg}	%d	F_{cg}	%d	F_{cg}	%d	F_{cg}	%d
0.71	70.68	0.31	87	0.34	54.82	0.87	29.75	0.5	53.02	0.34
0.79	70.9	–	87.3	–	55.3	–	29.9	–	53.2	–
0.87	71.16	0.37	87.58	0.37	55.64	0.61	30	0.33	53.39	0.36

Wheel radius, r_d (m) ($m_v = 14{,}515$ kg, $C_D = 0.79$)

–	Diesel Bus		CNG Bus	Hybrid Electric Bus			Electric Bus		Fuel Cell Bus	
r_d	F_{cg}	%d	F_{cg}	%d	F_{cg}	%d	F_{cg}	%d	F_{cg}	%d
0.45	68.64	3.19	84.04	3.73	53.45	3.35	29.47	1.44	52.59	1.15
0.5	70.9	–	87.3	–	55.3	–	29.9	–	53.2	–
0.55	71.29	0.55	90.14	3.25	56.38	1.95	30.33	1.44	53.65	0.85

indicate that an increase in any of the three selected variables negatively affects fuel consumption. It is important to note that these calculations were performed for the OCTA drive cycle, and the selected parameters may affect fuel consumption differently under other drive cycles.

4.3. Effect of road grade on the fuel consumption

Fuel consumption for various bus types was calculated on the modified CBD-14 drive cycle under fixed road grades (0 %, 2 %, and 4 %) with both A/C on and A/C off conditions. This approach aims to assess the effect of road grade on fuel consumption for each bus type under different A/C conditions. While the CBD-14 drive cycle does not typically incorporate road grade, ADVISOR allows for modifications to facilitate such analyses. Similar modifications to the different drive cycles have been employed in other studies to evaluate vehicle performance under inclined conditions [50]. Table 7 presents gasoline equivalent fuel consumption values for different bus types at various fixed road grades over the CBD-14 drive cycle.

Examining Table 7 reveals that across all road grades (0 %, 2 %, and 4 %), the CNG bus demonstrates the highest fuel consumption under both A/C on and A/C off conditions. However, when comparing the increase in fuel consumption as road grade rises, it becomes apparent that the HEB exhibits the smallest percentage increase in fuel consumption, indicating a relative advantage in terms of fuel efficiency over graded roads.

For the 2 % road grade specifically, the FCB displays the highest increase in fuel consumption, escalating by 78 % under A/C off conditions, while the EB experiences the highest increase (35.5 %) under A/C on conditions. Conversely, the CNG bus shows the smallest increase in fuel consumption under A/C off conditions, while the HEB demonstrates the least increase under A/C on conditions. Despite the lower increase in the HEB's fuel consumption, the electric bus remains the most fuel-efficient overall, showcasing the lowest absolute fuel consumption values at each road grade.

At the 4 % road grade, the results should be approached cautiously due to substantial discrepancies between the required and actual speeds for the diesel bus, CNG bus, and FCB, potentially affecting the accuracy of the fuel consumption data [49]. Nevertheless, under both A/C on and A/C off conditions, the hybrid electric bus again shows the smallest percentage increase in fuel consumption. Additionally, fuel consumption for the diesel, CNG, and fuel cell buses rises considerably, highlighting the impact of road incline on fuel demand in these bus types.

In summary, when considering both 2 % and 4 % fixed road grades, the hybrid electric bus appears more advantageous in terms of minimized fuel consumption increase. However, the electric bus consistently maintains the lowest fuel consumption across all scenarios, emphasizing its efficiency on graded roads.

Table 7
Fuel consumption (L/100 km, gasoline equivalent) for different fixed road grades.

	0 % road grade		2 % road grade		4 % road grade	
Bus Type	**A/C off**	**A/C on**	**A/C off**	**A/C on**	**A/C off**	**A/C on**
Diesel Bus	70.9	86.3	94.2	110.3	174.7*	208*
CNG Bus	88	102.7	114.3	134.2	215.3*	241.1*
Hybrid Electric Bus	52.9	58.6	71	73.3	78.7	80.2
Electric Bus	28	36.3	40.5	49.2	54	53.3
FCB	37.3	56.3	66.4	75.6	90.7	99.3*

* difference between the required and actual speeds is high (>10 %), the reliability of the results should be discussed.

4.4. Gradeability test

Gradeability tests were conducted at two different bus speeds, 20 km/h and 40 km/h. Table 8 presents the gradeability performance of the buses as a percentage for both A/C off and A/C on conditions. The most notable detail is that the hybrid electric bus consistently demonstrated the best performance in all scenarios. At 20 km/h, the bus with the highest gradeability was the hybrid electric bus, with 22.5 % for A/C off and 22 % for A/C on. The bus with the lowest performance was the FCB, with 12.2 % for both A/C off and A/C on. At 40 km/h, the hybrid electric bus again showed the highest gradeability, with 10.3 % for A/C off and 10.1 % for A/C on. The bus with the lowest performance was the FCB at 7.0 % for A/C off, and the CNG bus at 6.7 % for A/C on.

Table 8
Gradeability test for different bus speeds.

	20 km/h		40 km/h	
Vehicle Type	**A/C off**	**A/C on**	**A/C off**	**A/C on**
Diesel Bus	17.2 %	15.8 %	7.3 %	6.8 %
CNG Bus	17 %	15.5 %	7.1 %	6.7 %
Hybrid Electric Bus	22.5 %	22 %	10.3 %	10.1 %
Electric Bus	14 %	14 %	9.8 %	9.8 %
FCB	12.2 %	12.2 %	7.0 %	6.8 %

5. Conclusions

In this study, fuel consumption values for five different bus types (diesel, CNG, hybrid electric, electric, and fuel cell) were calculated using MATLAB/Simulink-based ADVISOR software across the OCTA drive cycle, considering both A/C on and A/C off conditions. Additionally, the effects of vehicle weight, aerodynamic drag coefficient, and wheel radius on fuel consumption were investigated. Subsequently, fuel consumption of different bus models was evaluated for a modified CBD-14 drive cycle under varying road grades (0 %, 2 %, and 4 %), with consideration of A/C activation status. Finally, gradeability tests were conducted. While the designs of the diesel and CNG buses were based on information from the literature [56], the hybrid electric bus, electric bus, and fuel cell bus were designed considering the EPA recommendations [58]. The validation of the ADVISOR model was performed by comparing the fuel consumption values of the diesel bus with those reported in the literature. The main findings from the study are as follows.

- Over the OCTA drive cycle, the lowest fuel consumption was observed in the electric bus under both A/C off and A/C on conditions, while the highest fuel consumption was recorded for the CNG bus in both scenarios. The increase in fuel consumption when the A/C was on compared to A/C off was most significant for the electric bus and least significant for the hybrid electric bus.
- The effects of bus weight, drag coefficient, and wheel radius on fuel consumption were analysed for the OCTA drive cycle. The results indicated that bus weight had the greatest impact on fuel consumption, while the drag coefficient had the least. Changes in bus weight had the most pronounced effect on the fuel consumption of the CNG bus, while the fuel cell bus showed the least sensitivity to weight variations. Alterations in the drag coefficient had the greatest impact on the fuel consumption of the hybrid electric bus, whereas the diesel bus exhibited the least responsiveness to changes in aerodynamic drag. Lastly, variations in wheel radius most significantly influenced the CNG bus, with the fuel cell bus being the least affected by changes in wheel radius.
- For the modified CBD-14 drive cycle, analyses conducted under varying fixed road grade values (0 %, 2 %, and 4 %) revealed that the CNG bus consistently exhibited the highest fuel consumption, whereas the electric bus demonstrated the lowest fuel consumption across all gradient values and under both A/C on and A/C off conditions, underscoring its superior fuel efficiency in gasoline equivalents across diverse operational scenarios. The hybrid electric bus demonstrated the smallest increase in fuel consumption as road grade increase.
- In the gradeability tests conducted at 20 km/h and 40 km/h, the hybrid electric bus exhibited the highest gradeability (22.5 % A/C off and 22 % A/C on), while the bus with the lowest performance was the fuel cell bus at 20 km/h (12.2 % A/C off and on) under both A/C off and A/C on conditions. At 40 km/h, the hybrid electric bus again showed the best gradeability performance (10.3 % A/C off and 10.1 % A/C on), FCB had the lowest performance under A/C off conditions (7.0 %), and the CNG bus had the lowest performance under A/C on conditions (6.7 %).

CRediT authorship contribution statement

Ahmet Fatih Kaya: Writing – original draft, Software, Methodology, Investigation, Data curation, Conceptualization. **Marco Puglia:** Writing – review & editing, Validation, Supervision. **Nicolò Morselli:** Writing – review & editing, Validation, Supervision. **Giulio Allesina:** Writing – review & editing, Validation, Supervision, Conceptualization. **Simone Pedrazzi:** Writing – review & editing, Visualization, Validation, Supervision, Software, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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