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Engines of Change: Comparison of Environmental Impacts Between Traditional Engines and Alternative Powertrains

Anqi Xi[1, *]

1High School Affiliated to Beijing Normal University, Beijing, China
*Corresponding author: angie_xi@outlook.com

Abstract:

This report provides a systematic assessment of the environmental influences associated with traditional internal combustion engine (ICE) cars, specifically spark ignition (SI) and compression ignition (CI) engines, and four consultant opportunity powertrains: hybrid electric motors (HEVs), plug-in hybrid electric vehicles (PHEVs), battery electric powered cars (BEVs), and fuel cell vehicles (FCVs). As the transportation sector continues to contribute about 29% of total U.S. greenhouse gas (GHG) emissions, identifying cleaner car technologies has become a pressing issue. The analysis adopts a well-to-wheel (WTW) approach, accounting not only for direct tailpipe emissions but also upstream emissions related to fuel production, power generation, and battery or hydrogen sourcing. The results show that while SI and CI engines emit significant levels of NOx, CO, HC, and particulate matter, hybrid and electric powertrains significantly reduce those pollutants, particularly BEVs and FCVs, which have zero tailpipe emissions. However, the overall sustainability of BEVs and FCVs hinges on the cleanliness of the electric grid and hydrogen production methods, respectively. Moreover, factors such as regenerative braking, energy recovery, driving styles, infrastructure availability, and lifecycle issues (e.g., battery production and disposal) affect actual-world performance. The report concludes that the transition to low-emission transportation should be coupled with decarbonization of the power supply. BEVs and FCVs powered by renewable sources constitute the most promising pathways towards sustainable mobility, while HEVs and PHEVs function as realistic transitional solutions. This work aims to provide comprehensive insight into powertrain-specific environmental trade-offs and to inform individual and policy-level decisions for more sustainable transportation options.

Keywords: Powertrain Comparison; Internal Combustion Engine; Battery Electric Vehicle; Fuel Cell Vehicle; Vehicle Emissions.

1. Introduction

In today's communication-based international environment, the transportation enterprise is liable for a significant percentage of greenhouse gas emissions. In line with the U.S. branch of strength, the transportation zone is responsible for 29% of the overall worldwide greenhouse gas (GHG) emissions within the United States as of the year 2021[1], indicating that vehicle emissions are playing a major role in contributing to global warming and accelerating environmental deterioration. As the global vehicle population is projected to increase—projected to exceed 2 billion by 2050—this trend is anticipated to worsen, especially in city regions wherein excessive automobile density is not the most effective contributor to long-term climate trade but also immediately impacts air quality, public health, and overall urban sustainability [2, 3]. Smog formation, noise pollution, and heat island effects are becoming increasingly more tied to fossil-gas-based transportation systems, underscoring the need for a shift closer to cleaner options. Expertise the environmental effects of more than one engine and choosing the proper automobile that generates the exceptionally lowest dangerous emissions and first-rate fits the user's desires has end up an essential trouble, now not only for the long-term preservation of our shared surroundings, however also for making sure the benefit, value-efficiency, and luxury of the drivers and passengers who represent a main a part of current society. In this context, it's far important to transport past comparing tailpipe emissions alone and instead undertake a more comprehensive well-to-wheel (WTW) approach—one which encompasses the full lifecycle of electricity manufacturing, distribution, and use [4]. This broader scope is specifically essential while assessing newer powertrain technologies, along with electric-powered and hydrogen-based structures, which may additionally shift emissions upstream depending on the electricity source used.

Currently, most conventional automobiles are prepared with spark ignition (SI) engines or compression ignition (CI) engines, with SI engines using sparks to ignite premixed combustion gasoline, even as CI engines depend upon high-pressure compression of air within the cylinder to provoke fuel ignition. Although both had been subtle for many years to attain reliability and performance, their dependence on fossil fuels remains incompatible with worldwide decarbonization desires, and their environmental externalities—ranging from greenhouse gases to neighborhood air pollution—are becoming increasingly more difficult to justify in light of available alternatives [5].

In this report, I'm able to conduct a scientific comparison of the tailpipe and lifecycle emissions of multiple automobile powertrains, examine their respective advantages and downsides under numerous actual-world situations, and outline key issues for deciding on a powertrain configuration that balances environmental impact with practicality.

2. Analysis of Multiple Engines and Comparing their Tailpipe Emission

In order to derive a specific view of the differences in environmental impacts of multiple engines, we need to firstly take a close look at the mechanisms of the different types of engines that are compared in the following paper. Identifying the characteristics of these kinds of engines can help us gain some insights into how they work exactly, how emissions are formed, and why they produce certain substances of emissions respectively.

2.1 SI&CI Engine

Being the two most common kinds of traditional engines, spark ignition engines and compression ignition engines are still common choices of powertrains that people choose when planning to purchase a vehicle. Although both use fuel combustion, their emissions differ.

2.1.1 Spark ignition engine

SI engines rely on a spark to ignite fuel. It typically uses four strokes to form a cycle of process to transform chemical energy stored in the gasoline into motion energy to support the operation of a car (Fig. 1). To be specific, a cycle of a four-stroke SI engine works as follows: first, air and the evaporated gasoline are mixed previously in the chamber guarded by the throttle valve; then, the premixed gas is moved to the cylinder; and when the piston moves up until a certain value of pressure is reached inside the chamber, the spark plug will be ignited and generates energy to give the piston a downward acceleration, which pushes the wheels to rotate and move the car forward. Under theoretical conditions, the mechanical efficiency of

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SI engines can reach up to 40%, while due to inevitable energy loss, such as through exhaust, the cooling process, and friction, it will output a mechanical efficiency of 20% to 25% [6].

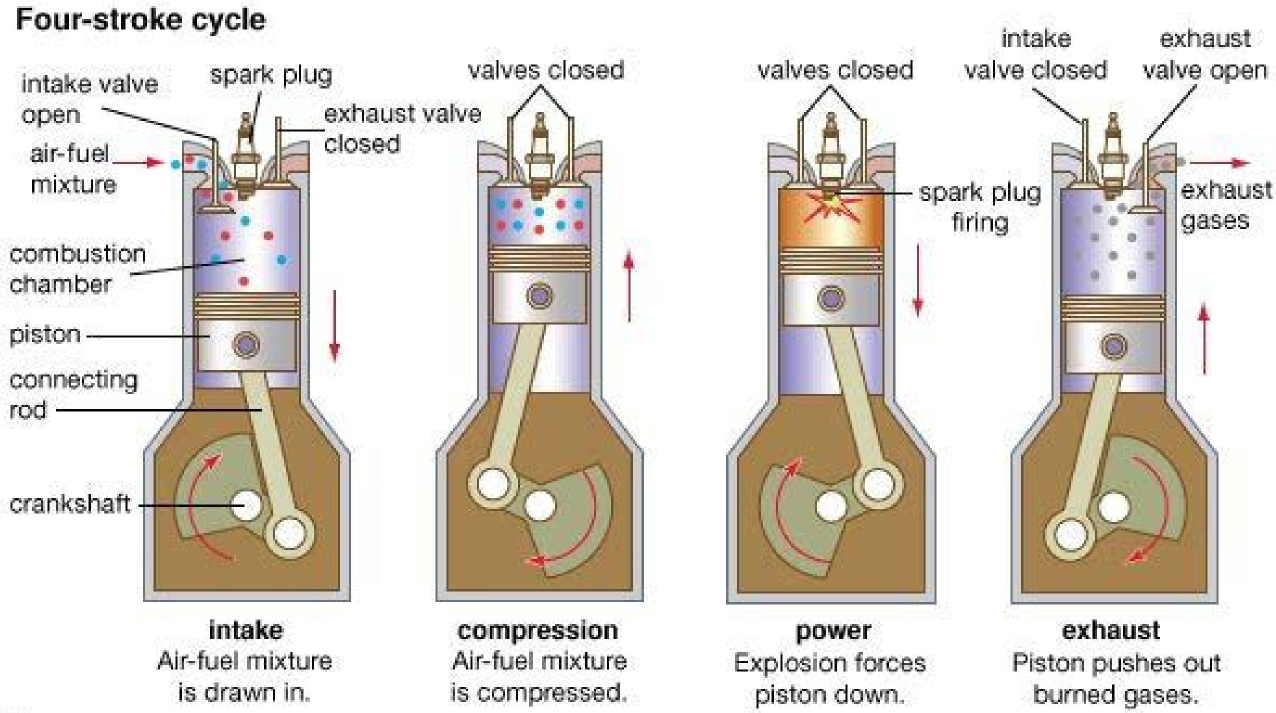

Fig.1 Internal-combustion engine: four-stroke cycle[7]

While generally efficient, SI engines release various kinds of harmful substances throughout their combustion process. Carbon monoxide (CO) is formed when the fuel experiences an incomplete combustion, especially when firing up at a cold temperature or when the premixed gas has a too high concentration, also known as a fuel-rich state. Hydrocarbons (HC) are emitted because the fuel was not completely ignited, possibly due to a cylinder wall misfire, uneven fuel injection, or insufficient combustion time under high rotation speed. Furthermore, under a hot combustion environment, the nitrogen in the air will react with oxygen to produce nitrogen oxides (NOx), another type of harmful chemical that takes a great part of the responsibility in the formation of smog, acid rain, and ground-level ozone. Even if traditional SI engines have relatively low emissions of particulate matter, the gasoline direct injection (GDI) engine, which has been widely adopted in recent years, emits a certain amount of ultrafine particulate matter under high load conditions or during acceleration, which can be a key contributor to air pollution.

2.1.2 Compression ignition engine

A compression ignition (CI) engine relies on the process of compression to ignite the fuel, rather than using a spark to produce thrust in a SI engine. During operation shown in Fig. 2, air first enters the cylinder through the intake valve and is then compressed due to the crankshaft's rotation, which drives the connecting rod to rise to a high temperature and high-pressure state as the piston moves upwards. Once this state is reached, the high-pressure common rail fuel injection system sprays diesel into the combustion chamber in a fine mist form. Due to the high temperature reached by compression, the diesel can spontaneously ignite without the need for a spark plug, as in a SI engine. The high-temperature and high-pressure gas produced by combustion then pushes the piston downwards, which in turn drives the crankshaft to rotate through the connecting rod, outputting mechanical energy. A compression ignition and spontaneous combustion method like this enables CI engines to have high thermal efficiency and stronger power output, making them widely used in heavy-duty vehicles, ships, and engineering equipment.

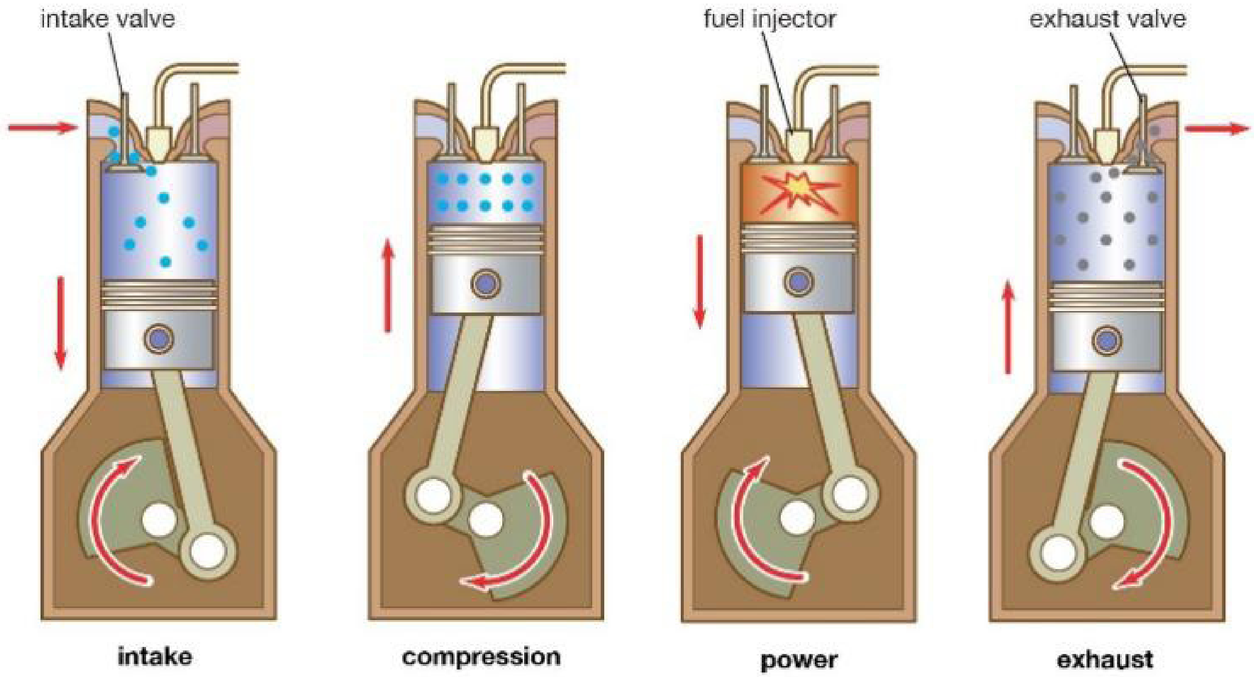

Fig.2 four-stroke diesel engine[8]

However, despite the high efficiency of CI engines, their combustion process also inevitably produces various air pollutants. Incomplete combustion of diesel fuel under low-temperature or localized hypoxia conditions generates carbon monoxide (CO) and hydrocarbons (HC); among them, HC mainly originates from unburned diesel in the cooling zone of the cylinder wall, at the end of fuel injection, or in the ignition delay area. In addition, due to the high combustion temperature and abundant oxygen in diesel engines, a large amount of nitrogen oxides (NOx) is easily formed in the combustion chamber, which are the main precursors that trigger photochemical smog and acid rain [9]. Moreover, incomplete combustion also leads to the formation of soot, which constitutes the main part of particulate matter (PM), in addition to the soluble organic fraction (SOF) and sulfate [10]. Similar to SI engines, especially during cold starts or high loads, these pollutant emissions increase significantly.

2.1.3 Similarities and differences

The primary distinction between spark-ignition (SI) and compression-ignition (CI) engines lies in how combustion is initiated. SI engines ignite a pre-mixed air–fuel blend using a spark plug, whereas CI engines inject diesel directly into highly compressed, hot air inside the cylinder, triggering autoignition. This fundamental contrast shapes not only their internal structure but also influences critical design aspects such as compression ratios, fuel management strategies, and combustion chamber geometry. These differences ultimately define each engine's emission profile and environmental characteristics [11].

CI engines generally offer higher thermal efficiency and deliver greater torque, especially under heavy-duty and prolonged workloads. In contrast, SI engines tend to be better suited for lighter applications, thanks to their quicker throttle response and ability to operate at higher RPMs. Furthermore, the ignition method gives SI engines more adaptability under varying driving conditions, whereas CI engines are often slower to respond to cold starts and rapid load changes. CI engines are able to maintain steady performance mainly at low speeds and under heavy loads, while SI engines are optimized for smooth operation at higher velocities.

2.2 Alternative Powertrains

Alternative powertrains of traditional engines include technologies designed to reduce environmental impact while still meeting transportation needs. These powertrains move away from full reliance on fossil fuels and often integrate electric propulsion or clean energy sources [12].

What I am going to cover in this report are four main types of alternative powertrains: hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), battery electric vehicles (BEVs), and fuel cell vehicles (FCVs). Each of these systems offers different approaches to reducing emissions and improving energy efficiency.

2.2.1 Hybrid powertrain

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Hybrid powertrains shown in Fig. 3 combine an internal combustion engine, typically a gasoline SI engine, with one or more electric motors and a battery storage unit, operate under a complex control strategy that seamlessly switches or blends power sources based on real-time driving conditions. This automatically shift between the spark ignition mode and electric power mode enables optimal energy utilization, specifically, relying primarily on the electric motor during low-speed [13], which is common in the stop-and-go urban driving condition and engaging the combustion engine for high-speed cruising or load-intensive acceleration when these performances are needed. This dual-source architecture not only improves fuel efficiency to 30% to 40% in average, reaching 40% for Toyota Prius, which is significantly more efficient than traditional SI engines. The high efficiency in this kind of powertrain is achieved by reducing the demand placed on the engine during inefficient operating ranges, while unfortunately, this property also enables regenerative braking, a mechanism that recaptures kinetic energy during deceleration and stores it in the battery, thereby enhancing overall system efficiency without compromising performance or driving comfort.

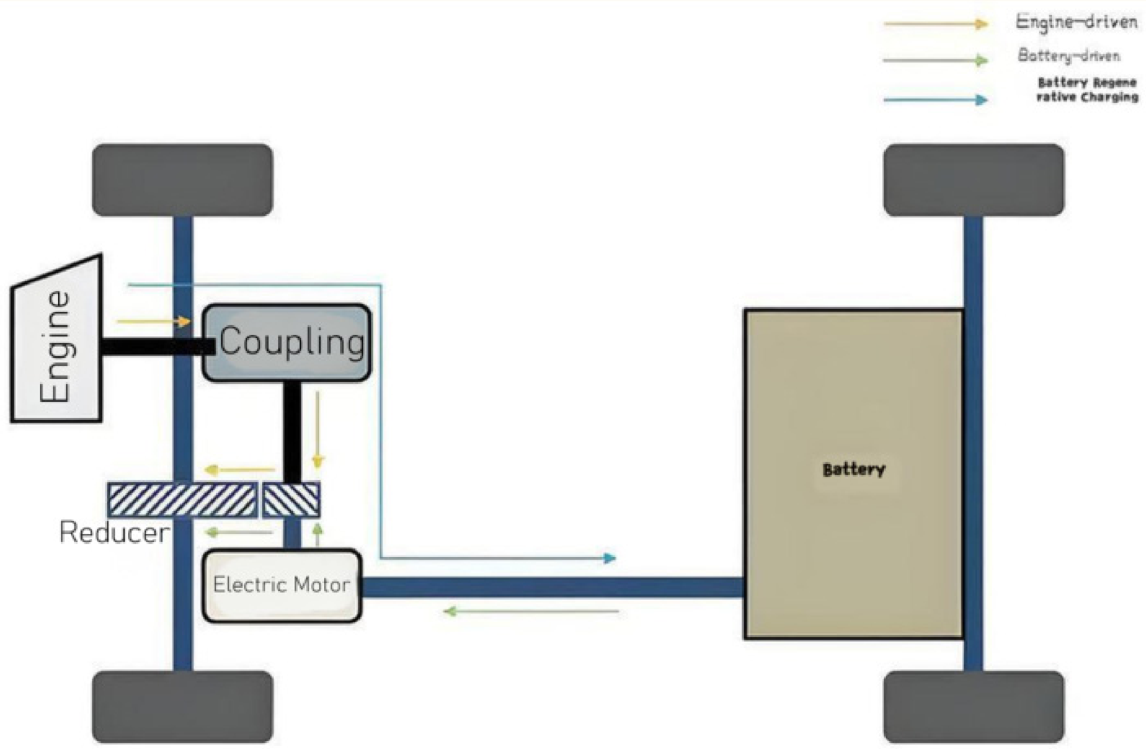

Fig.3 Structure of a hybrid powertrain [14]

Analyzing the dynamic performance of hybrid vehicles, they often exhibit smoother power delivery, quieter operation, and produce less emissions during typical driving cycles comparing to traditional internal combustion engines, particularly in traffic-congested environments, which is common in cities [15]; however, the presence of both electric and combustion systems increases the complexity, weight, and cost of the powertrain, and the environmental impact — though lower than traditional ICE vehicles — still depends on the fuel source of the combustion engine and the energy used for battery charging, so drivers of hybrid vehicles need to bear both the loading of gasoline and electricity in mind. Although cleaner than internal combustion engines, hybrids are often seen as a transitional solution rather than a fully clean alternative, as their emissions, while reduced, are not eliminated, and their lifecycle footprint, including battery production and disposal, also cannot be ignored.

2.2.2 Plug-in hybrid electric vehicle (PHEV)

Plug-in Hybrid Electric Vehicle (PHEV) shown in Fig. 4 powertrains are constructed upon the structure of conventional hybrid structures, integrating a larger-capacity, high-electricity-density battery pack—generally ranging from 10 to over 20 kWh—along with an onboard charging interface that allows outside grid charging, thereby permitting the automobile to operate in natural electric mode for prolonged distances (regularly 40 to 80 km or greater) without enticing the internal combustion engine. Structurally, the PHEV powertrain nonetheless incorporates a gasoline engine, one or more electric motors, a complex battery management system (BMS), a regenerative braking unit, and a power management module that coordinates energy flow throughout the system, frequently through sophisticated energy-split or parallel hybrid configurations. In contrast to traditional hybrid electric vehicles (HEVs), which depend completely on regenerative braking and engine-generated power to refill their small batteries, PHEVs allow drivers to recharge through domestic chargers or public Level 2/3 stations, making them far more practical for urban commuters who seek zero-emission riding for short- to medium-range journeys.

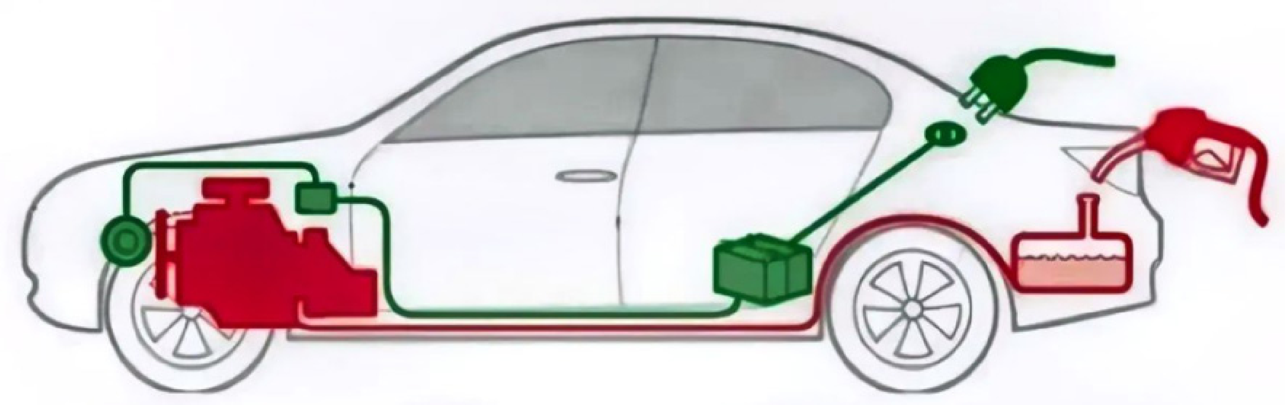

Fig.4 Structure of a PHEV [16]

In terms of energy strategy and system control, PHEVs provide additional operational flexibility: they can perform in natural EV mode for low-speed, short-distance travel, switch to hybrid mode when battery power runs low or energy demand increases, and many models also offer driver-selectable settings such as cost-saving or energy-saving modes, in which the engine is used primarily on highways to conserve battery charge for city driving. Furthermore, due to their larger motor output and more robust battery systems, PHEVs usually offer higher acceleration performance than general hybrids; for example, models like the Toyota RAV4 Prime, BMW X5 xDrive45e, or BYD Tang DM-p feature combined outputs exceeding 200 kW and achieve 0–100 km/h times in under 6 seconds. The overall mechanical efficiency of advanced PHEVs can reach 36–38% or more, as compared to 30–32% for traditional HEVs like the Toyota Prius, whose smaller batteries and weaker automobiles make them more reliant on the gasoline engine and less perfect to common quick journeys in urban prevent-and-pass situations.

2.2.3 Battery electric vehicle (BEV)

Different from hybrid powertrains and PHEV powertrains, battery electric automobiles (BEVs) depend entirely on electricity saved in excessive-potential lithium-ion or robust-country batteries to electricity electric powered motors. They achieve extremely high energy conversion efficiency by eliminating the inherent thermodynamic losses in the internal combustion process. Therefore, they produce zero tailpipe emissions within the path of operation, making them attractive solutions to decrease air pollution and greenhouse gas emissions. Thanks to its simple and responsive design that eliminates transmissions and engine vibrations, BEV's electric drivetrain delivers smooth acceleration and instant torque, which might be a problem when shifting modes between the internal combustion engine and electric engine in a hybrid vehicle or a PHEV, thus significantly improving the driving experience while reducing maintenance and long-term costs.

Although BEVs produce zero tailpipe emissions, they still face several challenges: driving range, charging infrastructure, and electricity sources. While contemporary batteries have advanced in energy density and charging pace, variety anxiety remains a problem—specially in regions with confined public chargers or in bloodless climates that lessen battery overall performance. Additionally, the actual environmental advantages of BEVs heavily depends on the carbon depth in the energy grid: in regions where fossil fuels dominate power generation, upstream emissions may partly offset their zero-emission advantage. Problems about raw cloth extraction, battery recycling, and surrender-of-life manipulate additionally enhance environmental and ethical problems that want to be addressed to completely gather their sustainability capacity.

2.2.4 Fuel cell vehicle (FCV)

Fuel cell vehicles (FCVs) has a high-pressure tank with hydrogen as its fuel. It operates by converting hydrogen into electricity through an electrochemical reaction with oxygen in a fuel cell stack. Since the transformation is a process that produces only water vapor as a byproduct, it allows the vehicle to achieve zero tailpipe emissions while

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delivering smooth and quiet operation similar to that of a battery electric vehicle. The electricity is generated on demand to power an electric motor, allowing for efficient and responsive driving without relying on combustion or large batteries. Its fast refueling and long-range capacity make it especially suitable for long-distance or commercial use, which is somewhat restricted electric powertrains.

Since the energy conversion process of FCVs are totally clean, the environmental impacts of FCVs depend on how hydrogen is produced — fossil fuel-based methods generate significant emissions, while renewable-powered electrolysis is nearly carbon-neutral. However, high system costs, limited refueling infrastructure, energy demands for hydrogen storage and transport, and safety concerns are all drawbacks that are hindering their large-scale adoption [17]. Additionally, the complexity of establishing a hydrogen economy—from production and storage to end-user distribution—requires coordinated investments and policies that are currently under development but not yet mature enough for large-scale deployment.

2.3 Emissions Comparison Overview

Table 1 compare the emissions of all types of powertrains mentioned above, including from tailpipe emissions to total WTW emission. Gasoline and diesel engines still produce the most emissions, especially harmful gases like NO_x, CO, and HC. Hybrids and plug-in hybrids reduce these significantly, especially in urban use. BEVs and FCVs offer the cleanest drive-time performance, although upstream factors like electricity and fuel production must be considered.

Table 1 Comparison overview of various powertrain types [18, 19]

Powertrain Type	Tailpipe Emissions	Upstream Emissions	Total WTW Emissions
SI Engine (Gas)	High	Moderate	Very High
CI Engine (Diesel)	High	Moderate	Very High
HEV	Moderate	Moderate	High
PHEV	Low (city use)	Moderate to High	Moderate
BEV (coal grid)	Zero	High	High
BEV (clean grid)	Zero	Low	Low
FCV (from natural gas)	Zero	High	High
FCV (green hydrogen)	Zero	Low	Low

3. Well-to-Wheel Emissions

Tailpipe emissions don't tell the whole story. A vehicle's environmental cost includes what happens before the fuel reaches the tank or the battery is charged. Gas-powered vehicles create emissions from drilling and refining oil, as well as transporting fuel. These steps increase the total greenhouse gases linked to driving [20]. For BEVs, the focus shifts to battery production and electricity generation. Mining lithium and other metals uses a lot of energy. The cleaner the grid, the lower the total emissions of a BEV. FCVs depend on how hydrogen is produced. Right now, most hydrogen comes from natural gas, which still emits CO_2. If hydrogen can be made using renewable electricity, FCVs could become a much greener option.

4. Conclusion

Even though internal combustion engines remain dominant in the vehicle market now, the momentum behind cleaner powertrains is building, and a trend of using cleaner powertrains is taking place. Battery electric vehicles and fuel cell vehicles are leading the way in terms of reducing emissions during operation, especially when paired with renewable energy.

Choosing the right powertrain involves more than checking the tailpipe. It requires looking at where the energy comes from and how it's made. Cleaner transportation depends on improving not just the vehicles, but also the energy systems behind them. In fact, the crucial feature of a clean mechanism of a powertrain is shifting from the emissions it produces when running to the method of how the fuel is derived and processed.

In addition to environmental protection, electric vehicles also bring convenience. Many cities are investing in more public charging points, and home charging is becoming easier for drivers with off-street parking. For daily commuting and short trips, most electric vehicles offer more than enough range. They're also quiet, smooth to drive, and need less upkeep—no oil changes, fewer moving parts, and less brake wear. All of this adds up to make electric cars not only cleaner, but also simpler to live with. For city drivers in particularly, it is a smart and sustainable choice.

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