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Drive Cycle And Temperature Impact On The Performance Of Fuel Cell Electric And Internal Combustion Engine Vehicles Using Advisor

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Abstract: The transportation sector significantly contributes to global greenhouse gas emissions and urban pollution, primarily from fossil-fueled internal combustion engine vehicles (ICEVs). As sustainable alternatives, fuel cell electric vehicles (FCEVs) offer high efficiency, zero tailpipe emissions, and compatibility with renewable hydrogen. This study uses ADVISOR simulation software to compare the performance of a fuel cell vehicle and a conventional gasoline-powered ICEV across five drive cycles (UDDS, HWFET, FTP, EUDC, INRETS) and three ambient temperatures. Key metrics include energy efficiency, fuel (hydrogen and gasoline) consumption, and emissions. Results show the FCEV achieves higher efficiency—over 41% during highway driving—while the ICEV reaches about 21% efficiency in highway conditions. The FCEV's hydrogen economy improves at elevated temperatures. The ICEV maintains fairly constant fuel use but emits significant pollutants, notably hydrocarbons, carbon monoxide, nitrogen oxides, and particulate matter, especially during urban and cold-start conditions. Findings highlight FCEVs' potential to reduce pollution and support decarbonization, contingent on clean hydrogen production and infrastructure. The study underscores the need for policies and technologies to accelerate fuel cell vehicle adoption in India's transportation sector.

Index Terms - Fuel Cell Electric Vehicle (FCEV), Internal Combustion Engine Vehicle (ICEV), ADVISOR, Hydrogen Consumption, Energy Efficiency, Emissions, Drive Cycles.

I. Introduction

The transportation sector is one of the most energy-intensive components of modern society and a major source of global environmental degradation. It contributes nearly 24% of direct CO_2 emissions from fuel combustion worldwide (IEA, 2023). In India, vehicular emissions significantly deteriorate urban air quality and pose serious public health risks. The heavy dependence on Internal Combustion Engine Vehicles (ICEVs), powered by gasoline and diesel, is central to this issue. With thermal efficiencies of only 20–30%, ICEVs waste most of the fuel energy as heat while releasing harmful pollutants such as carbon monoxide (CO), nitrogen oxides (NO_x), hydrocarbons (HC), and particulate matter (PM). These emissions intensify climate change, photochemical smog, and respiratory health concerns, underlining the need for sustainable mobility solutions.

Battery Electric Vehicles (BEVs) have emerged as one such alternative, offering zero tailpipe emissions and reduced petroleum dependence. However, their drawbacks include long charging times, limited range in certain models, efficiency loss at extreme temperatures, and environmental concerns associated with large battery production and recycling. In India, additional challenges such as limited charging infrastructure, grid reliability, and long-distance travel demand restrict large-scale BEV adoption.

Fuel Cell Electric Vehicles (FCEVs), powered by hydrogen, present a promising solution. Unlike BEVs that rely on stored electricity, FCEVs generate electricity on board through Proton Exchange Membrane Fuel Cells (PEMFCs), producing only water vapor and heat as by-products. This technology provides key advantages, including short refueling times (3–5 minutes), long driving ranges comparable to ICEVs, and reduced dependence on critical mineral-intensive batteries. PEM fuel cells achieve efficiencies of 40–60%, significantly higher than ICEVs. Furthermore, when hydrogen is produced via renewable pathways such as wind- or solar-powered electrolysis, FCEVs can achieve near-zero well-to-wheel emissions, positioning them as a sustainable mobility pathway.

Despite these benefits, barriers such as high costs, limited hydrogen infrastructure, and safety concerns persist. Nonetheless, countries including Japan, South Korea, Germany, and the United States are investing heavily in hydrogen mobility. India has also initiated the National Green Hydrogen Mission to promote hydrogen adoption in transport and other sectors.

In this context, it becomes important to evaluate ICEVs and FCEVs under comparable conditions to highlight differences in efficiency, fuel/hydrogen consumption, and emissions. Since real-world testing is costly, simulation tools like ADVISOR (Advanced Vehicle Simulator**)** offer an effective approach to study vehicle performance across diverse driving cycles and ambient temperatures. This study employs ADVISOR to conduct a comparative analysis of FCEVs and ICEVs over five standard drive cycles (UDDS, HWFET, FTP-75, EUDC, INRETS) and three temperatures (10°C, 30°C, 45°C), focusing on efficiency, hydrogen/fuel use, and emissions.

II. LITERATURE REVIEW

The transportation sector's impact on global emissions has motivated extensive research into alternative powertrains. Recent studies have focused on evaluating the environmental and operational performance of Internal Combustion Engine Vehicles (ICEVs), Battery Electric Vehicles (BEVs), and Fuel Cell Electric Vehicles (FCEVs).

Alrashydah et al. [1] demonstrated that ICEVs emit high levels of CO_2, NO_x, and particulate matter, while BEVs offer significant reductions when coupled with renewable energy. Fuel cell technologies, particularly Proton Exchange Membrane Fuel Cells (PEMFCs), have been reviewed extensively for automotive applications, showing high power density, moderate operating temperature, and rapid transient response, though challenges remain in durability and cost [2]. Optimal fuel cell stack sizing has been shown to balance efficiency, durability, and lifecycle performance [3], while integrating waste heat recovery systems can further improve overall energy efficiency [8].

Simulation-based studies provide valuable insights into vehicle performance. Shivappriya et al. [4] and Chiver et al. [7] used the ADVISOR tool to evaluate BEV efficiency across different drive cycles and environmental conditions, highlighting the role of driving patterns and ambient temperature. Attia et al. [5] compared BEVs and FCEVs, noting BEVs' higher short-range efficiency but FCEVs' advantages for long-range and heavy-duty applications. Duan et al. [6] and Vural et al. [9] emphasized that real-world driving cycles increase hydrogen consumption compared to standardized laboratory cycles. Liang and Wu [10] further explored tri-source hybrid FCEV systems, demonstrating improved efficiency, durability, and component longevity through integrated energy management.

Collectively, these studies underscore the potential of FCEVs as a sustainable alternative to ICEVs, particularly when renewable hydrogen is used, and highlight the importance of drive-cycle and environmental considerations in performance evaluation.

III. METHODOLOGY

The present study employs a simulation-based approach to compare the performance of Fuel Cell Electric Vehicles (FCEVs) and Internal Combustion Engine Vehicles (ICEVs). The methodology integrates vehicle modeling, drive cycle definition, and simulation of varying temperature conditions using the Advanced Vehicle Simulator. ADVISOR is a MATLAB/Simulink-based tool developed by the U.S. National Renewable Energy

Laboratory (NREL) for analyzing conventional, hybrid, battery, and fuel cell vehicles. It has been extensively validated for powertrain research and offers built-in libraries of vehicle components, customizable control strategies, and standard drive cycles (Markel et al., 2002; NREL, 2002). Its capability to model both energy consumption and emission behavior under real-world conditions makes it highly suitable for comparative performance analysis.

3.1 Simulation Environment Setup

ADVISOR was installed as a MATLAB toolbox and launched using the advisor command in the MATLAB environment. Upon launch, the ADVISOR main menu provides access to the vehicle input window, where the user can select and configure vehicle type, powertrain, drivetrain, and component models. From this interface, the FCEV and ICEV models were defined for subsequent simulations.

3.2 Vehicle Configuration

In this study, two vehicle models were configured in ADVISOR: a Fuel Cell Electric Vehicle (FCEV) and an Internal Combustion Engine Vehicle (ICEV). Component selection was carried out through the vehicle input window, where each subsystem such as the fuel converter, energy storage, motor, transmission, accessories, and control modules was defined to represent realistic mid-size passenger vehicles suitable for both urban and highway operation.

The FCEV model (Figure 1) employed VEH_SMCAR as the vehicle body, representing a small passenger car architecture with a total mass of 1159 kg including a 136 kg cargo load, and configured for front-wheel drive. The primary energy source was a hydrogen fuel cell system (FC_ANL50H2), rated at 70 kW net power with approximately 60% peak efficiency and a mass of 283 kg. A lithium-ion battery module (ESS_LI7) consisting of 30 cells at 320 V and weighing 34 kg was incorporated to support regenerative braking and peak power demands, with the state-of-charge initialized at 0.85. Propulsion was provided through a permanent magnet synchronous motor (MC_PM49) rated at 52 kW with 96% efficiency, coupled to a single-speed transmission (TX_1SPD) of 50 kg. Accessory loads were modeled using ACC_HYBRID to account for HVAC, lighting, and steering, while regenerative braking was enabled with WH_SMCAR_REGEN. Power management was governed by the PTC_FUELCELL control strategy, which allocated steady-state loads to the fuel cell, peak demands to the battery, and enabled energy recovery during deceleration. This configuration reflects a typical mid-size FCEV optimized for both urban and highway driving.

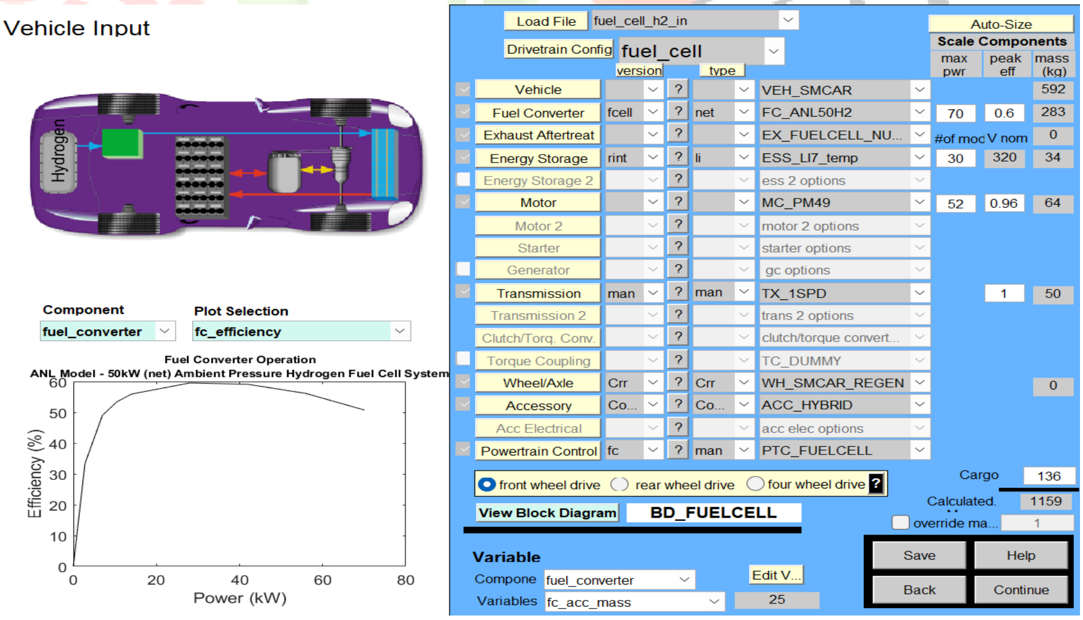


Figure 1: ADVISOR Vehicle Input Window for FCEV Configuration

The ICEV model (Figure 2) also adopted the VEH_SMCAR platform, with a total calculated mass of 1039 kg including a 136 kg cargo load, and configured for front-wheel drive. The propulsion source was a diesel engine (FC_CI67_emis), simulating a Volkswagen 1.9L turbocharged engine rated at 54 kW net output, achieving about 40% peak efficiency with a mass of 181 kg. An exhaust aftertreatment system (EX_CI) with a mass of 16 kg was included to ensure emissions compliance by reducing engine-out pollutants. Unlike the FCEV, no dedicated energy storage was modeled, consistent with conventional ICEV operation. The drivetrain incorporated a five-speed manual transmission (TX_5SPD) weighing 114 kg, allowing the engine to operate efficiently under varied conditions. The WH_SMCAR module was used to simulate rolling resistance and torque transfer, while accessory demands were represented by ACC_CONV to include HVAC, lighting, and steering. Vehicle operation was managed through the PTC_CONV control module, which coordinated gear shifting and throttle modulation to balance performance with fuel economy. This configuration reflects a standard small, diesel-powered passenger vehicle suitable for realistic urban and highway operations.

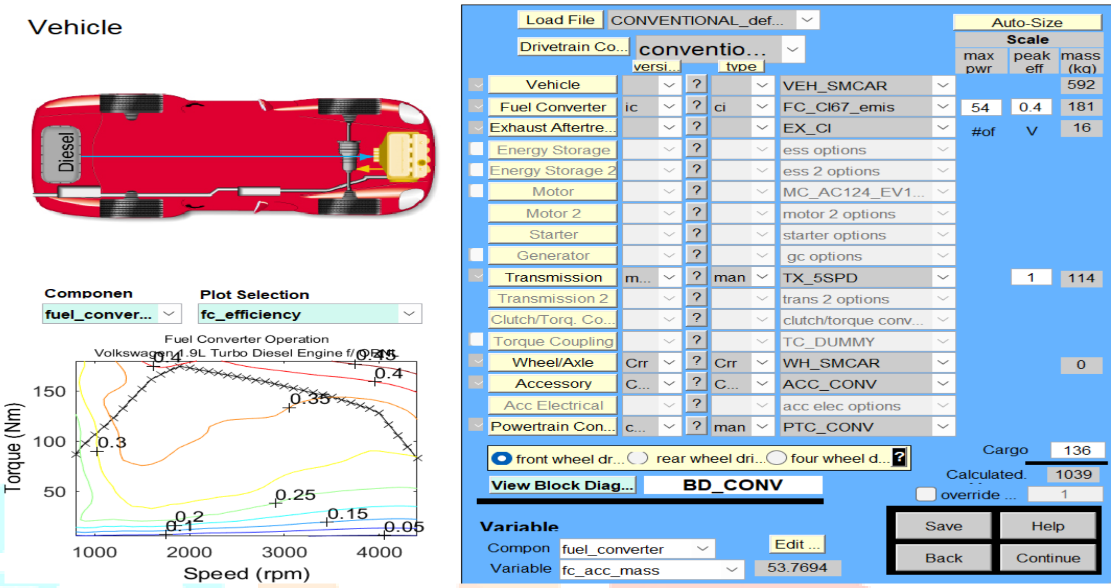


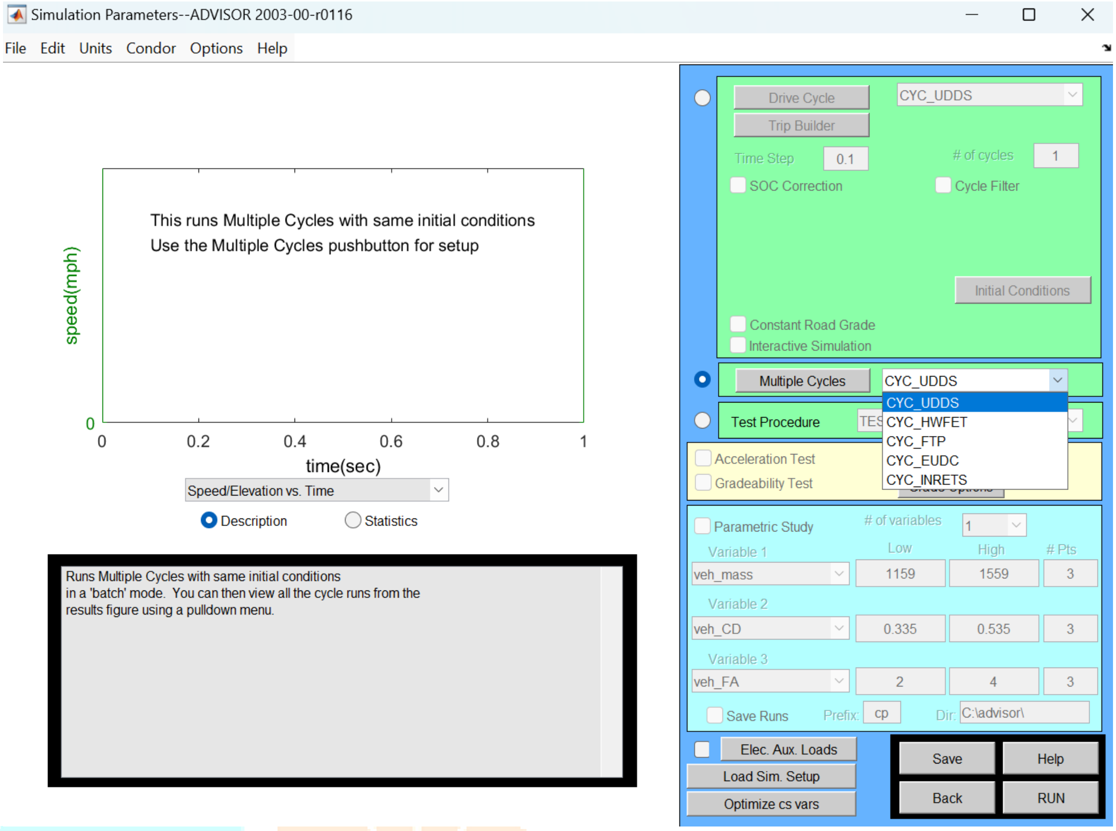
Figure 2: ADVISOR Vehicle Input Window for ICEV Configuration

The configurations described above ensure that both the FCEV and ICEV models are represented with realistic and comparable setups, allowing a fair evaluation of their performance under identical test conditions. By standardizing the vehicle body platform while varying only the powertrain architecture, the study isolates the impact of propulsion technology on efficiency, fuel/hydrogen consumption, and emissions. With the vehicle models established, the next step involves defining the drive cycles that replicate real-world operating conditions, as discussed in next section.

3.3 Simulation Setup and Drive Cycle Execution

After finalizing and saving the Fuel Cell Electric Vehicle (FCEV) and Internal Combustion Engine Vehicle (ICEV) configurations described in Section 3.2, both vehicle models were subjected to performance evaluation within the Simulation Parameters window of ADVISOR. The objective was to assess the effect of different standardized drive cycles and ambient temperature conditions in a uniform and reproducible manner.

To accomplish this, the Multiple Cycles option in ADVISOR was selected, enabling sequential execution of predefined drive cycles without altering the simulation setup between runs. This feature ensured consistency of test conditions and comparability of results across both vehicle models.



. **Figure 3.** Simulation Parameters window in ADVISOR illustrating the configuration of standard drive cycles (UDDS, HWFET, FTP-75, EUDC, and INRETS) employed for simulating FCEV and ICEV performance.

3.3.1 Drive Cycles

Five standardized drive cycles were employed to capture a broad spectrum of real-world driving patterns. These cycles are widely recognized in vehicle performance research and regulatory testing:

- **UDDS (Urban Dynamometer Driving Schedule):** Represents stop-and-go urban driving characterized by frequent accelerations and decelerations at low speeds.
- **HWFET (Highway Fuel Economy Test):** Simulates steady-state highway operation, emphasizing fuel economy under cruising conditions.
- **FTP-75 (Federal Test Procedure):** A composite cycle combining urban and highway phases, representative of typical mixed driving in the United States.
- **EUDC (Extra-Urban Driving Cycle):** A European test cycle with higher average and maximum speeds than UDDS, reflecting peri-urban and inter-urban driving conditions.
- **INRETS (Institut National de Recherche sur les Transports et leur Sécurité):** A French urban traffic cycle characterized by short acceleration bursts, frequent idling, and dense traffic conditions.

The representative speed-time profiles of these cycles are illustrated in Figure 4, while their key statistical parameters are summarized in Table 1.

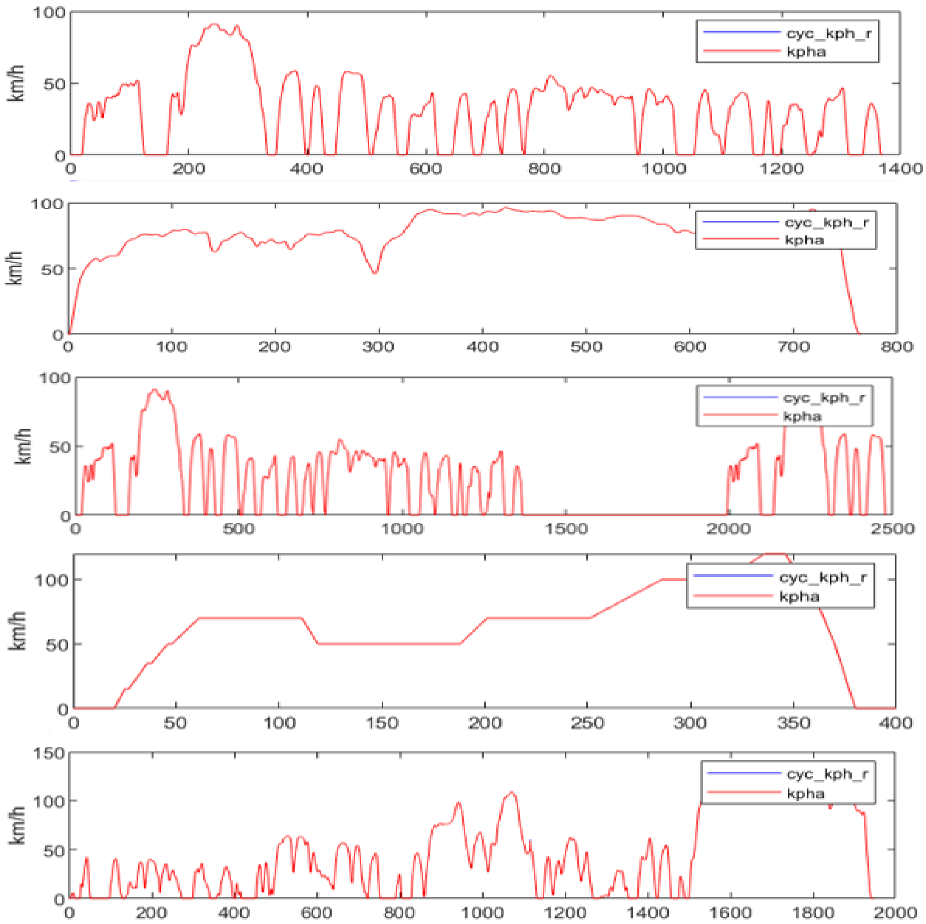


Figure 4: Drive cycle speed–time profiles used in the study. From top to bottom: (a) UDDS, (b) HWFET, (c) FTP-75, (d) EUDC, and (e) INRETS

Table 1. Statistical parameters of selected drive cycles

Drive Cycle	Duration (s)	Avg. Speed (km/h)	Max. Speed (km/h)	Distance (km)
UDDS	1369	31.5	91.25	11.99
HWFET	765	77.58	96.4	16.51
FTP-75	2477	25.82	91.25	17.77
EUDC	400	62.44	120	6.95
INRETS	1947	46.45	128.75	25.12

3.3.2 Initial Conditions

To ensure controlled and comparable results, initial conditions were defined prior to each simulation run using the ADVISOR Initial Conditions window, as shown in Figure 5. These conditions included:

- **Ambient temperature (amb_tmp):** Varied at 10 °C, 30 °C, and 45 °C to represent cold-start, moderate, and hot climate scenarios.
- **Battery state-of-charge (SOC):** Fixed at 0.85 for all runs to provide a uniform energy baseline for FCEV simulations.
- **Component temperatures:** Fuel cell stack, motor, and exhaust components were initialized at the same ambient temperature for each run to maintain thermal consistency.

By systematically varying the ambient temperature while maintaining all other initial states constant, the influence of environmental conditions on fuel economy, efficiency, and emissions could be isolated and analyzed.

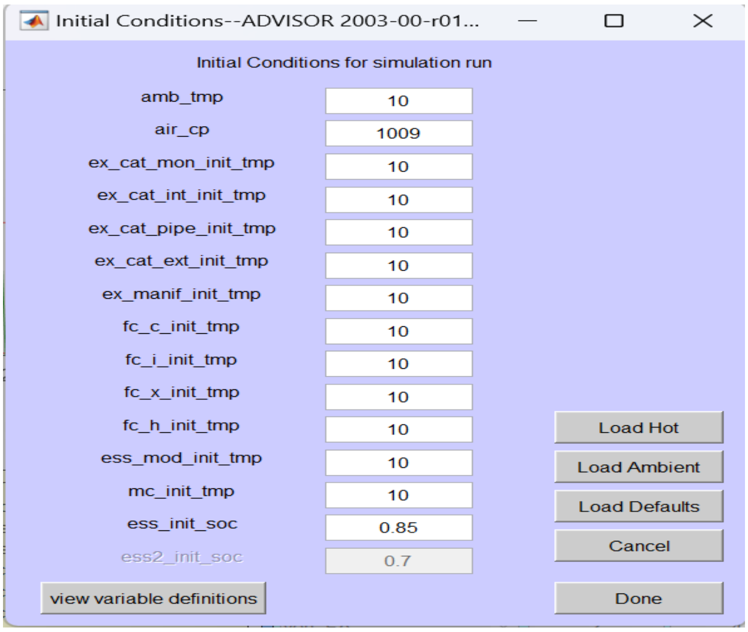


Figure 5. Initial Conditions window in ADVISOR

3.3.3 Simulation Protocol

Each vehicle model (FCEV and ICEV) was subjected to the same protocol:

1. Execution of all five drive cycles sequentially at 10 °C ambient temperature.
2. Repetition of the same five cycles at 30 °C.
3. Final repetition of the five cycles at 45 °C.

This resulted in a total of 15 simulation runs per vehicle, ensuring robust comparative data across varying driving and environmental conditions.

Notably, the acceleration test, gradeability test, and parametric study modules available in ADVISOR were deliberately excluded, as the scope of this study is limited to vehicle-level performance under standardized drive cycles and temperature variations.

Thus, Section 3.3 established a standardized simulation framework in ADVISOR, incorporating five representative drive cycles and three controlled ambient temperature conditions for both FCEV and ICEV models. By fixing component initial states and applying a uniform execution protocol, the methodology ensured comparability of results across different vehicle types and operating environments. With the simulation setup complete, the next step is to define the performance metrics—efficiency, fuel/hydrogen consumption (in L/100 km), and emissions (for ICEV)—that form the basis of result evaluation, as discussed in Section 3.4.

3.4 Performance Metrics

The simulation results for the Fuel Cell Electric Vehicle (FCEV) and the Internal Combustion Engine Vehicle (ICEV) were evaluated based on key performance indicators that directly reflect energy efficiency, fuel consumption, and emissions. These metrics were selected to provide a comprehensive comparison of both vehicle types under standardized drive cycles and varying ambient temperature conditions.

3.4.1 Vehicle Efficiency

Efficiency was computed as the ratio of useful traction energy delivered at the wheels to the total energy input from the fuel source (hydrogen for FCEV and diesel for ICEV).

- For FCEV, efficiency accounted for conversion losses in the fuel cell stack, energy storage interactions, and traction motor operation.
- For ICEV, efficiency was derived from engine brake-specific fuel consumption (BSFC) maps and transmission losses.

This metric allows a direct comparison of how effectively each powertrain converts its respective fuel into propulsion energy across different drive cycles.

3.4.2 Fuel Consumption

Fuel consumption was normalized to liters per 100 kilometers (L/100 km) for both vehicle types to ensure consistent comparability.

- **Hydrogen consumption (FCEV):** Recorded as the cumulative hydrogen flow from the fuel cell stack during each drive cycle, expressed in L/100 km (gaseous hydrogen at standard conditions).
- **Diesel consumption (ICEV):** Calculated from the fuel flow rate of the internal combustion engine, also expressed in L/100 km.

This approach enables a clear representation of the relative fuel economy of both vehicles under identical operating conditions.

3.4.3 Emissions (ICEV Only)

Since the fuel cell system produces zero tailpipe emissions, only the ICEV was assessed for regulated pollutants. The ADVISOR emissions module provided cumulative mass outputs of:

- **CO_2 (g/km):** Indicator of greenhouse gas contribution.
- **NO_x (g/km):** Linked to air quality degradation and smog formation.
- **HC (g/km):** Represents unburned hydrocarbons released due to incomplete combustion.
- **Particulate Matter (PM, g/km):** Associated with respiratory health concerns in urban environments.

These emissions were recorded for each drive cycle at all three ambient temperature conditions, enabling a detailed evaluation of ICEV environmental impact relative to the zero-emission profile of FCEVs.

3.4.4 Summary of Metric Selection

The chosen metrics—efficiency, fuel consumption, and emissions—establish a robust framework for comparison. Efficiency provides insight into energy utilization, fuel consumption quantifies real-world operating cost and range implications, while emissions highlight environmental sustainability.
The outcomes of these evaluations are systematically presented in Chapter 4 (Results and Analysis**).**

IV: RESULTS AND ANALYSIS

This chapter presents the simulation results obtained from ADVISOR for both Fuel Cell Electric Vehicle (FCEV) and Internal Combustion Engine Vehicle (ICEV) configurations. Simulations were carried out across five drive cycles (UDDS, HWFET, FTP-75, EUDC, and INRETS) under three ambient temperature conditions (10 °C, 30 °C, and 45 °C).

To avoid redundancy, only two representative simulation plots are shown: one for the FCEV and one for the ICEV under UDDS drive cycle at 10 °C. These plots illustrate the type of outputs generated in ADVISOR, including speed tracking, state of charge (SOC) variation, fuel consumption, and emission profiles. The complete dataset for all drive cycles and temperatures is summarized in tabular form for clarity and compactness.

4.1 Fuel Cell Electric Vehicle (FCEV) Results

Figure 6 shows the ADVISOR results for the FCEV on the UDDS cycle at 10 °C. The vehicle achieved a distance of 12 km with a hydrogen consumption of 33.4 L/100 km. As expected, all emissions (HC, CO, NOx, PM) are zero, since FCEVs produce only water vapor as a byproduct. The state of charge (SOC) profile indicates the contribution of the battery during transient load demands, particularly during acceleration phases.

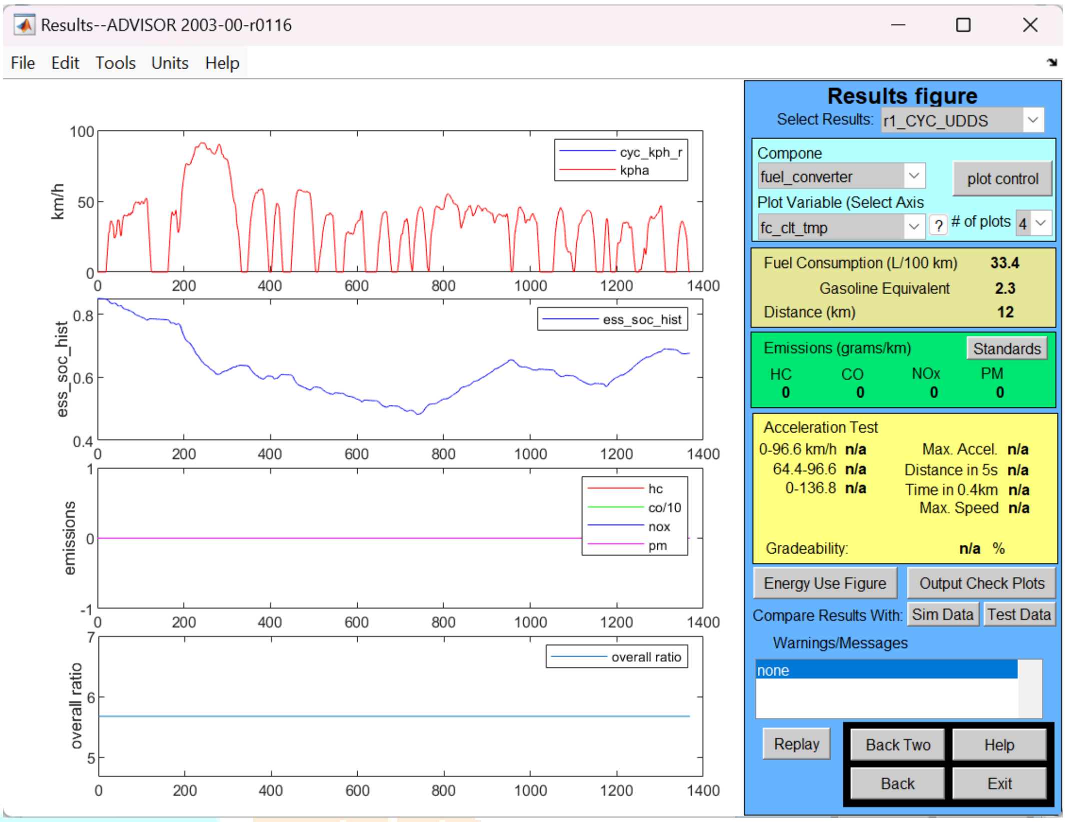


Figure 6: ADVISOR result for FCEV on UDDS cycle at 10 °C

The overall FCEV efficiency at this condition was 22.2%. As discussed later, efficiency improves significantly at higher temperatures, due to reduced warm-up energy demand and better fuel cell operating conditions.

4.3 Internal Combustion Engine Vehicle (ICEV) Results

Figure 7 presents the ADVISOR simulation results for the ICEV on the UDDS cycle at 10 °C. The vehicle consumed 4.9 L/100 km of fuel over the 12 km test distance. In contrast to the FCEV, the ICEV exhibited significant tailpipe emissions: HC = 0.278 g/km, CO = 0.606 g/km, NOx = 0.378 g/km, and PM = 0.033 g/km. These values are consistent with the expected emission behavior under cold-start conditions, where incomplete combustion and catalyst warm-up delays lead to higher pollutant formation.

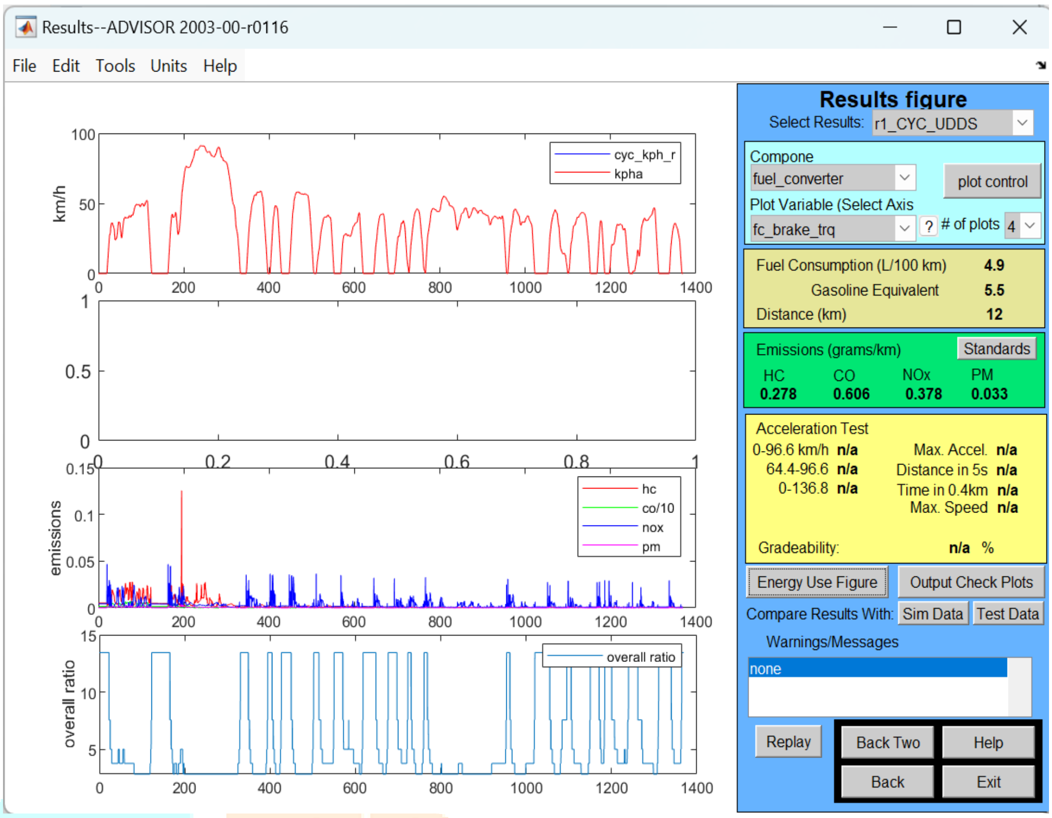


Figure 7: ADVISOR result for ICEV on UDDS cycle at 10 °C

The ICEV efficiency at this condition was 10.2%, less than half of the FCEV value, highlighting the superior energy conversion capability of fuel cells compared to conventional internal combustion engines.

4.4 Tabulated Results for All Drive Cycles and Temperatures

Table 2: Comparison of FCEV and ICEV Efficiency (%) across Drive Cycles and Temperatures

Drive Cycle	**Temperature (°C)**	**FCEV Efficiency (%)**	**ICEV Efficiency (%)**
UDDS	10	22.2	10.2
	30	25.4	10.3
	45	31.2	10.3
HWFET	10	40.7	20.9
	30	41.5	20.9
	45	41.9	21.0
FTP-75	10	26.1	11.2
	30	27.2	11.3
	45	28.3	11.3
EUDC	10	36.4	18.6
	30	37.5	18.7
	45	37.9	18.7
INRETS	10	33.5	16.2
	30	34.3	16.3
	45	34.3	16.3

Table 3: Fuel Consumption of FCEV and ICEV (Hydrogen L/100 km vs Fuel L/100 km)

Drive Cycle	Temperature (°C)	FCEV (H_2 L/100 km)	ICEV (Fuel L/100 km)
UDDS	10	33.4	4.9
	30	25.4	4.8
	45	12.4	4.8
HWFET	10	26.5	4.0
	30	26.1	4.0
	45	25.6	3.9
FTP-75	10	26.9	4.8
	30	25.3	4.8
	45	23.4	4.8
EUDC	10	33.0	4.4
	30	32.5	4.4
	45	32.0	4.4
INRETS	10	40.8	5.7
	30	39.7	5.7
	45	40.0	5.7

Table 4: ICEV Emissions across Drive Cycles and Temperatures (g/km)

Drive Cycle	Temperature (°C)	HC (g/km)	CO (g/km)	NOx (g/km)	PM (g/km)
UDDS	10	0.278	0.606	0.378	0.033
	30	0.209	0.507	0.371	0.028
	45	0.163	0.431	0.371	0.025
HWFET	10	0.136	0.266	0.279	0.028
	30	0.096	0.211	0.288	0.027
	45	0.072	0.171	0.289	0.025
FTP-75	10	0.209	0.481	0.380	0.030
	30	0.161	0.409	0.374	0.027
	45	0.129	0.354	0.374	0.025
EUDC	10	0.461	0.928	0.350	0.049
	30	0.316	0.718	0.380	0.043
	45	0.216	0.564	0.395	0.039
INRETS	10	0.195	0.472	0.730	0.052
	30	0.144	0.366	0.718	0.048
	45	0.109	0.291	0.710	0.046

4.5 Comparative Analysis of FCEV and ICEV Performance

The simulation results presented in Tables 2– 4 provide a comprehensive comparison between Fuel Cell Electric Vehicles (FCEVs) and Internal Combustion Engine Vehicles (ICEVs) under different drive cycles (UDDS, HWFET, FTP-75, EUDC, and INRETS) and temperature conditions (10 °C, 30 °C, 45 °C). A detailed comparative analysis is discussed below:

1. **Efficiency Trends**
   - FCEVs consistently exhibited higher efficiency than ICEVs across all drive cycles and temperature conditions.
   - The efficiency gap was particularly significant in urban driving conditions (UDDS and FTP-75), where frequent acceleration and deceleration favor the regenerative braking and optimal operating behavior of the fuel cell system.

- At elevated ambient temperatures (45 °C), FCEV efficiency improved further, owing to reduced auxiliary power demand for cold-start and thermal management. ICEVs, however, showed minimal improvement in efficiency across temperature variations.

2. **Fuel Consumption vs. Hydrogen Consumption**
    - FCEVs demonstrated a clear reduction in hydrogen consumption with rising ambient temperatures. For example, hydrogen consumption at 10 °C was highest, reflecting additional energy required during cold-start operation. At 30 °C and 45 °C, hydrogen use declined significantly, enhancing overall economy.
    - In contrast, ICEV fuel consumption remained comparatively stable, with only marginal reductions across different temperatures. This highlights the temperature sensitivity of FCEVs and the relative insensitivity of ICEVs to ambient conditions in terms of fuel usage.

3. **Emission Profiles**
    - FCEVs recorded zero tailpipe emissions (HC, CO, NOx, PM) under all conditions, reinforcing their potential as environmentally sustainable alternatives.
    - ICEVs produced considerable emissions across all cycles, with HC, CO, and NOx levels peaking in urban cycles (UDDS, FTP-75) due to frequent transients and incomplete combustion events. PM emissions, although lower than gaseous pollutants, were still consistently present.
    - Increasing ambient temperature did not significantly reduce ICEV pollutant emissions, highlighting the persistent environmental drawbacks of conventional ICE technology.
4. **Temperature Impact**
    - The effect of ambient temperature was more pronounced on FCEVs than ICEVs. While ICEVs remained relatively insensitive to temperature variation, FCEVs showed marked performance gains at 30 °C and 45 °C, both in terms of efficiency and hydrogen economy.
    - Cold-start conditions (10 °C) were most challenging for FCEVs, leading to higher hydrogen use and slightly reduced efficiency, though still superior to ICEVs.
5. **Overall Comparison**
    - The comparative results strongly suggest that FCEVs outperform ICEVs in efficiency and emission characteristics under all tested scenarios.
    - Although ICEVs currently demonstrate more stable fuel consumption patterns across varying temperatures, their high emissions profile makes them environmentally unsustainable.
    - FCEVs, despite higher sensitivity to temperature, remain the more efficient and eco-friendly option, particularly when operated in moderate to warm climates.

CONCLUSION

This study investigated the comparative performance of Fuel Cell Electric Vehicle and Internal Combustion Engine Vehicle using the ADVISOR simulation platform. Five representative drive cycles—UDDS, HWFET, FTP-75, EUDC, and INRETS—were evaluated at three ambient temperatures (10°C, 30°C, and 45°C) to replicate real-world driving conditions and climatic variations. The performance metrics focused on vehicle efficiency, fuel or hydrogen consumption, and tailpipe emissions.

The results clearly demonstrate that FCEVs consistently outperformed ICEVs in terms of efficiency. While ICEVs operated within the narrow range of 10–21%, FCEVs exhibited higher values between 22% and 42%, with maximum efficiency achieved during highway cycles at elevated temperatures. The influence of ambient temperature was more pronounced in FCEVs, where warm conditions enhanced electrochemical performance and reduced thermal losses, whereas ICEVs displayed only marginal temperature sensitivity due to the stable but inherently inefficient combustion process.

Fuel utilization trends further highlighted the differences between the two vehicle types. Hydrogen consumption in FCEVs varied widely across cycles (12.4–40 L/100 km), depending on load transients and ambient temperature. In contrast, ICEVs showed relatively stable consumption (4–5.7 L/100 km). Despite the higher volumetric consumption of hydrogen, normalization by energy density and conversion efficiency confirmed the superior energy economy of FCEVs.

The most significant distinction emerged in the emissions domain. FCEVs achieved zero tailpipe emissions, producing only water vapor, whereas ICEVs released hydrocarbons, carbon monoxide, nitrogen oxides, and particulate matter in considerable quantities. Emissions were highest under transient urban cycles and at low temperatures, with CO peaking at 0.928 g/km (EUDC, 10°C) and NOx at 0.73 g/km (INRETS, 10°C).

Although emissions reduced slightly at higher ambient temperatures, they remained significant, underlining the environmental impact of ICEVs.

Overall, the findings confirm the technological and environmental superiority of FCEVs. Their higher efficiency and absence of harmful emissions directly address the critical challenges of energy security and air pollution. While ICEVs continue to dominate due to existing infrastructure and lower initial costs, their long-term sustainability is severely limited.

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