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E-Heater Performance for Aftertreatment Warm-Up in a 48V Mild-Hybrid Heavy-Duty Truck over Real Driving Cycles

Praveen Kumar *, Rafael Lago Sari, Ashish Shah  and Brock Merritt

Aramco Americas, Aramco Research Center, Detroit, MI 48377, USA;
rafael.lagosari@aramcoamericas.com (R.L.S.); ashish.shah@aramcoamericas.com (A.S.);
brock.merritt@aramcoamericas.com (B.M.)

* Correspondence: praveen.kumar@aramcoamericas.com

Abstract: High-efficiency and low-emissions heavy-duty (HD) internal combustion engines (ICEs) offer significant GHG reduction potential. Mild hybridization via regenerative braking and enabling the use of an electric heater component (EHC) for the aftertreatment system (ATS) warm-up extends these benefits, which can mitigate tailpipe GHG and NO_x emissions simultaneously. Understanding such integrated hybrid powertrains is essential for the system optimization of real-world driving conditions. In the present work, the potential of a low engine-out NO_x (1.5–2.5 g/kWh range) ‘Low-NO_x’ HD diesel engine and EHCs were analyzed in a 48V P1 mild-hybrid system for a class 8 commercial vehicle concept and compared with those in an EPA-2010-certified HD diesel truck as a baseline under real-world driving cycles, including those from the US, Europe, India, China, as well as the world harmonized vehicle cycle (WHVC). For analysis, an integrated 1-D vehicle model was utilized that consisted of models of the ‘Low-NO_x’ HD engine, the stock ATS, and a production EHC. For the real driving cycles, ‘GT-RealDrive’-based vehicle speed profiles were generated for busy trucking routes for different markets. For each cycle, the effects of the Low-NO_x and EHC performances were quantified in terms of the ATS warm-up time, engine-out NO_x emissions, and net fuel consumption. Depending on the driving route, the regenerative braking fully or partly neutralized the EHC power penalty without a significant impact on the ATS thermal performance. For a two-EHC system, the fueling penalty associated with every second reduction in the warm-up time FC_{EHC} (g/s) was several-fold higher for the real driving routes compared with the WHVC. Overall, while a multi-EHC setup accelerated the ATS warm-up, a single EHC integrated at the SCR inlet showed minimized EHC heating power, leading to a minimized fueling penalty. Finally, for the India and China routes, being highly transient, the P1 hybridization proved inadequate for GHG reduction due to the limited energy recuperation. A stronger hybridization was desirable for such driving cycles.

Keywords: electric heater; 48V; hybrid; heavy-duty; low-NO_x; warm-up; aftertreatment; engine



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1. Introduction

On-road heavy-duty (HD) trucks and buses account for nearly 35% of direct CO₂ emissions worldwide [1]. With the current economic growth trends, the global HD truck fleet is expected to increase approximately 2.5 times, reaching over 60 million vehicles by 2050 [2]. To effectively curb the rising greenhouse gas (GHG) emissions from on-road transport, regulatory agencies are imposing increasingly stringent targets globally. The US Environmental Protection Agency (EPA) is mandating 15% and 30% reductions in CO₂ emissions by 2027 and 2030, respectively, compared to the 2019 levels [3]. Similarly, the European Parliament has adopted CO₂ reduction targets of 45% by 2030, 65% by 2035, and 90% by 2040 [4] for commercial vehicles. Following the European standards, China’s VI regulations [5] require a NO_x 0.46 g/kWh limit, while India has mandated the Bharat Stage (equivalent to EU standards) limits [6].

With regard to meeting future regulatory requirements for commercial transport, fully electric powertrains do not offer favorable economics [7,8]. The use of low-carbon fuels for internal combustion engines (ICEs), hybridization, and a combination of both can potentially mitigate CO₂ emissions [9]. In the meantime, existing HD diesel engines and aftertreatment systems (ATSs) must continue to advance for a reduced GHG impact. If tailored for hybridization, HD propulsion systems can potentially meet the interim 2027 ultra-low NO_x of 0.02 g/kWh [10] and 30% GHG reduction targets by 2030 and facilitate a seamless transition into future carbon-neutral vehicle powertrains when ready.

Using hybridization, the traditional trade-offs of increased fuel requirements and reduced NO_x emissions for diesel engines [11,12] can be decoupled. For low NO_x emissions, recent combustion advances, such as low-temperature combustion (LTC) concepts via high exhaust gas recirculation (EGR) levels, have demonstrated low engine-out NO_x emissions (Low-NO_x) and improved fuel efficiency simultaneously [13,14]. In addition, hybrid propulsion systems have allowed the use of more efficient subsystems, such as electrified boost systems, EGR pumps, and other auxiliary components, that further extend fuel efficiency and emissions benefits [15–19].

One of the key challenges for using the ‘Low-NO_x’ concept is the excessive dilution requirement [20,21], which causes reduced exhaust gas temperatures, leading to a deteriorated ATS performance. Therefore, for HD hybrid powertrains, Advanced ATS configurations and effective exhaust thermal management are imperative for compliance with the tailpipe NO_x emissions limits, particularly at low-load and cold ambient operations [22–25]. To that end, the use of an electric heater component (EHC) can accelerate the selective catalytic reduction (SCR) catalyst warm-up [26], making it a low-cost system compared with alternatives like burner [27,28] and dynamic skip fire (DSF) concepts [29].

Earlier, Lindemann et al. [30] demonstrated an SCR warm-up time reduction of over 60% using a 10 kW EHC over the world harmonized transient cycle (WHTC). Similarly, Meruva et al. [31] integrated a 7 kW EHC upstream from a close-coupled SCR followed by the main SCR system, which helped meet the CARB’s 2027 NO_x 0.02 g/kWhr target for HD engines. Later, EHC-integrated powertrain studies focused on optimizing the EHC power rating and SCR thermal performance. Kasab et al. [32] showed a 1% additional fueling penalty for the added EHC upstream of a close-coupled SCR, which satisfied the 2027 CARB standards with a 10% margin. Subsequently, Webb et al. [33] experimented using a 4 kW EHC for a 13 L HD engine over the low-load cycle (LLC) and noted a 7% fueling penalty for emissions compliance. To further minimize EHC-associated fueling penalties, Brin et al. [34] used turbine bypassing along with the EHC, which demonstrated a ~50 °C hotter exhaust temperature and low fuel consumption for the first 400 s of the EPA-regulated HD federal test procedure (HDFTP) cycle. Furthermore, using cylinder deactivation and a 5 kW rated EHC together, Matheaus et al. [35] demonstrated a 1.5% lower fuel consumption compared with the EHC alone. Further optimization showed an additional 50% reduction in EHC power consumption for similar NO_x levels [36].

Thus far, the potential of EHCs has been demonstrated for over-regulated certification cycles, with a negligible understanding of the EHC performance requirements for advanced ‘Low-NO_x’ HD engines over commercial trucks in real-world driving conditions. The performance of an EHC must be examined in terms of its ATS warm-up time reduction and net fueling penalty. This trade-off examination, across real-world driving cycles, is of high importance in HD engine manufacturing to select the appropriate EHC rating and hybridization degree for emissions compliance and to minimize the total operating costs.

Therefore, in this work, the potential of a low engine-out NO_x (1.5–2.5 g/kWh range) (Low-NO_x) HD diesel engine and EHCs were analyzed in a 48V P1 mild-hybrid system over the world harmonized vehicle cycle (WHVC) and the real driving cycles for major global markets, including the US, Europe, India and China. The objectives of this study were the following:

1. First, analyze the ATS warm-up time’s impact using a ‘Low-NO_x’ HD engine, compared to an EPA 2010-certified HD diesel truck as a baseline (Base).

2. Evaluate different EHC-integrated ATS configurations using a P1 hybrid powertrain for the ATS warm-up time reduction, EHC power penalty, and regenerative energy.
3. Identify the best HD hybrid powertrain configuration in terms of the lowest ATS warm-up time and net fuel consumption for each region.

2. 1-D Vehicle Simulation Methodology

2.1. Vehicle Modeling

A GT-SUITE [37] based 0-D/1-D 48V mild-hybrid electric vehicle (MHEV) model was developed to represent a class 8 VOLVO VNL 760 long-haul truck. Figure 1 shows the schematic of the 1-D MHEV model. For hybridization, a P1 topology was applied due to its favorable cost-to-performance trade-off for commercial vehicles. In the P1 configuration, the electric motor was coupled to the engine crankshaft, allowing torque-assist (e-assist) events and promoting regenerative braking via engine crank decelerations.

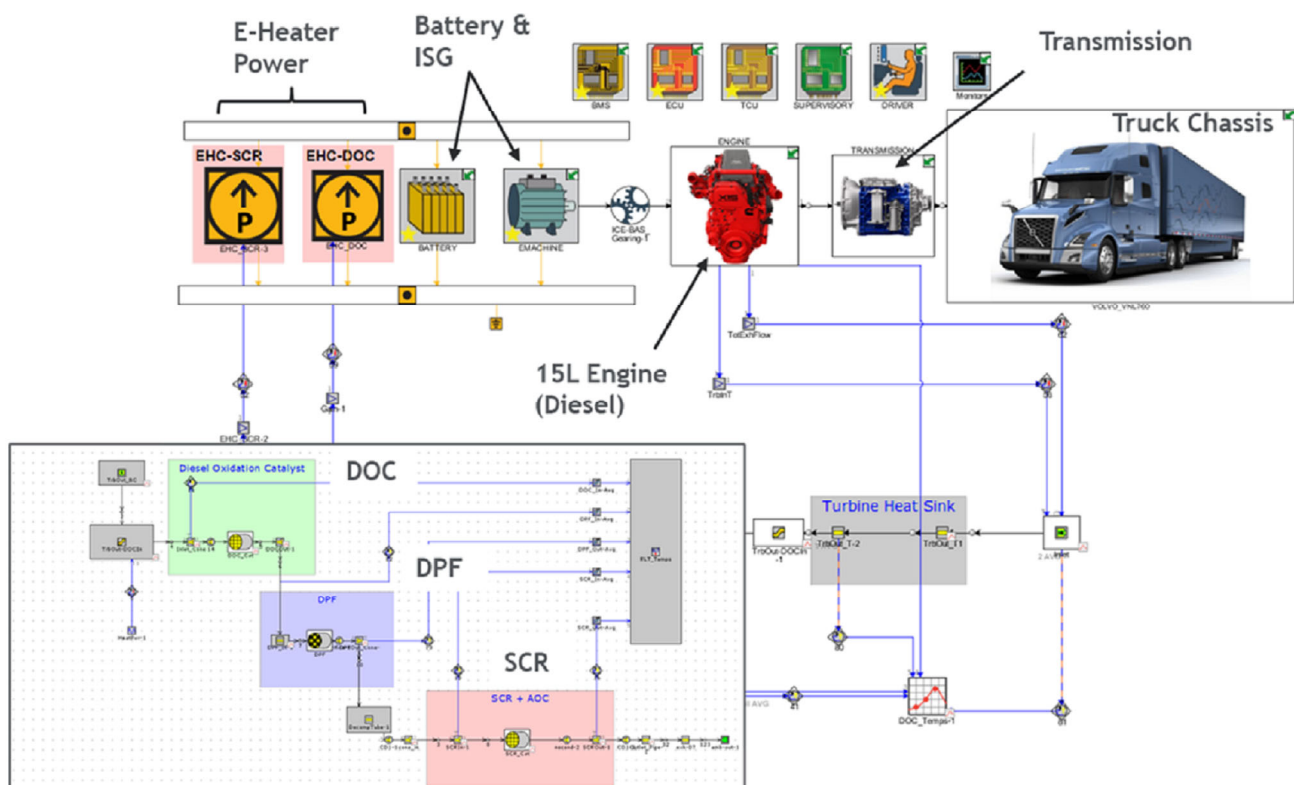


Figure 1. Schematic of detailed 0-D/1-D vehicle model.

The modeled vehicle specifications are listed in Table 1. For the P1 MHEV, a 6.8 kWh battery system and a stock-integrated starter generator (ISG) with a rating of 105 Nm and a peak efficiency of 88% (from the literature [38,39]) were used. Table 2 shows key details of the 48V P1 configuration. The details of the HD engine, aftertreatment system (ATS), and electric heater component (EHC) modeling are discussed in the subsequent sections.

Table 1. Primary vehicle parameters.

Vehicle Specifications	
Engine	15 L Diesel
Vehicle weight [kg]	8730
Drag coefficient [-]	0.62
Vehicle frontal area [m ²]	6.5
Gross vehicle weight rating [kg]	36,250

Table 1. *Cont.*

Vehicle Specifications	
Vehicle wheelbase [m]	5.5
Rolling friction [-]	0.007
Tires specification	295/80R/22.5
Gearbox models	ATO2612F
Differential drive ratio	2.28

Payload → assumed 100% in the study for most conservative scenarios.

Table 2. P1 Hybrid configuration details.

48V P1 MHEV Specifications	
ISG max. motor [kW]	20 (88% Peak Eff)
Initial battery [kWh]	6.8
Final gear ratio [-]	2.25
Max. crate 5 s [-]	20
Max. crate t > 10 s [-]	7
Reg. braking	yes
e-drive	no
e-assist	yes

For the P1 MHEV operation, a supervisory control was imposed with modifications in the states and transition logics to manage the EHC operation and battery state-of-charge (SOC) recovery together. Table 3 lists the states and the transition logics. Over a driving cycle, starting from the state S1 (vehicle stop and engine off), the vehicle was allowed to transition to the S2 state (engine cranking) and then move to S3 (idle and support battery charging), S4 (idle and power EHC for ATS warm-up), or S5 (idle and no additional loading). Once engine idling was not required, the vehicle was mandated to return to S1 or further move to S6 (vehicle cruising). In the S6 state, the engine acted as the primary propulsion source with an e-assist from the ISG motor when the power request exceeded the engine's peak power rating. During coasting, the engine fueling was turned off, and the vehicle was allowed to transition to S7 (ISG engaged for brake energy regeneration), S8 (ISG engaged and EHC active), or S9 (ISG disengaged, EHC inactive, and SOC at the maximum limit), as needed.

Table 3. Vehicle supervisory control.

	Control States				
	S1 (Veh. Stop)	S2 (Eng Start)	S3-S4-S5 (Idling)	S6 (Cruising)	S7-S8-S9 (Coasting)
VehSpd Speed (V)	V = 0	V = 0	V = 0	V > 0	V = 0
EngSpd (RPM)	RPM = 0	RPM > 0	RPM > Idle	RPM > Idle	RPM = 0
Engine On/Off	0	0	1	1	0
Engine Load	0	0	Idle Load	Driver Req.	0
ISG	0	Load (crank)	Load (Battery Charge)	0	Load (Crank)
EHC	0	0	0 or 1	0	0 or 1
Pedal Pos.	100	100	100	Driver	100

2.2. Engine and ATS Modeling

An EPA-2010-certified Cummins ISX15 HD diesel engine was simulated for the MHEV HD truck, with the key details shown in Table 4.

Table 4. Diesel engine specifications.

‘Base’ Engine Specifications	
Stroke [mm]	169
Bore [mm]	137
Number of cylinders [-]	6
Displaced volume [L]	14.9
Air-handling system	Single-stage VGT turbo and cooled ext. EGR
ATS system	DOC, DPF, and SCR
Rated power	336 kW @ 1800 rpm
	2375 Nm @ 1000 rpm

DOC—diesel oxidation catalyst; DPF—diesel particulate filter; EGR—exhaust gas recirculation; SCR—selective catalyst reduction; VGT—Variable-geometry turbocharger.

For the P1 MHEV modeling, the HD engine was simulated by imposing 2-D lookup tables/maps for fueling, pre-turbine exhaust temperature, and engine-out emissions (including NO, CO, and CO₂), similar to previous studies [8,16]. These 2-D maps were generated from the steady-state measurements on the HD engine dynamometer. The ‘Base’ ISX15 HD engine exhibited an engine-out NO_x range of 3–4.8 g/kWh, categorized as ‘High-NO_x’. Subsequently, a low engine-out NO_x range of 1.5–2.5 g/kWh HD engine (Low-NO_x) was developed. The conversion from the ‘Base’ engine to the Low-NO_x version mandated engine hardware iterations, including both the combustion and the air-handling systems [12–14,20]. Figure 2a–c illustrate the differences in the engine-out NO_x (Δ NO_x, expressed as a percentage or fraction), the exhaust temperature (Δ Exh T, in °C), and the fuel consumption (Δ FC, as a percentage or fraction) measurements over the EPA’s 13-mode supplemental emissions test (SET) cycle between the ‘Low-NO_x’ and the ‘High-NO_x’ HD engines. The ‘Low-NO_x’ engine achieved a 75% reduction in the NO_x emission levels while incurring ~55 °C colder exhaust temperatures and an additional 3.5–14% fuel consumption, compared to the ‘Base’.

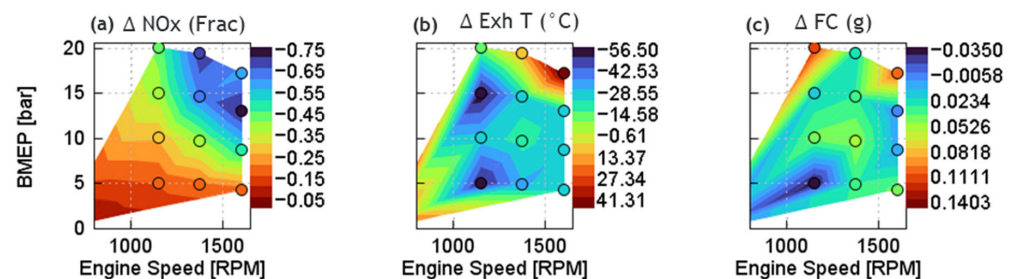


Figure 2. Differences in (a) NO_x, (b) Exh T, and (c) fuel consumption (FC) between the High-NO_x and Low-NO_x calibration for the HD diesel engine. The ‘o’ marker represent the ‘The 13-mode SET cycle’ engine operations.

For the aftertreatment system (ATS) modeling, predictive 1-D thermal models were developed for the subcomponents, including the diesel oxidation catalyst (DOC), diesel particulate filter (DPF), and selective catalyst reduction (SCR). These models were verified using experimental data. The model calibration, following literature [8], involved tuning the heat transfer coefficient ‘h’. For the gas-to-wall interaction, the ‘h’ value was correlated with the exhaust flow and its specific heat, whereas a constant ‘h’ value of 20 W/m²·K was imposed for the wall-to-ambient interaction. The catalyst wall was modeled as a lumped system, considering its relatively small thickness. Unfortunately, due to proprietary concerns, specific geometric and washcoat details of the ATS components could not be disclosed. Figure 3a–c illustrate the model’s correlation with measurements for the DOC, DPF, and SCR temperatures over the HDFTP cycle. The predictive ATS model performed well during the certified HDFTP cycle and was later used for performance characterization of the ATS across different drive cycles.

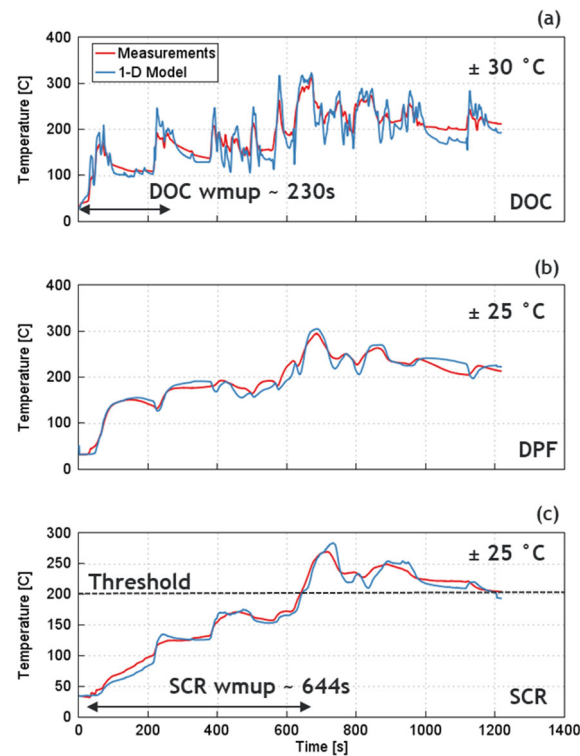


Figure 3. ATS model correlation with the measurements over the HDFTP cycle for (a) DOC, (b) DPF, and (c) SCR.

To predict the turbine-out temperature (TrbOut T), it was crucial to characterize the impact of the turbine's thermal inertia. For this purpose, a lumped thermal mass object represented the turbine housing (including the volute, wheel, and shaft). The lumped mass's heat capacity and the gas-to-wall 'h' at the turbine inlet were calibrated using measurements from the cold and the hot HDFTP transient cycles. Figure 4a,b demonstrated that the turbine-lumped thermal mass model closely matched the measurements during the cold and hot cycles, respectively.

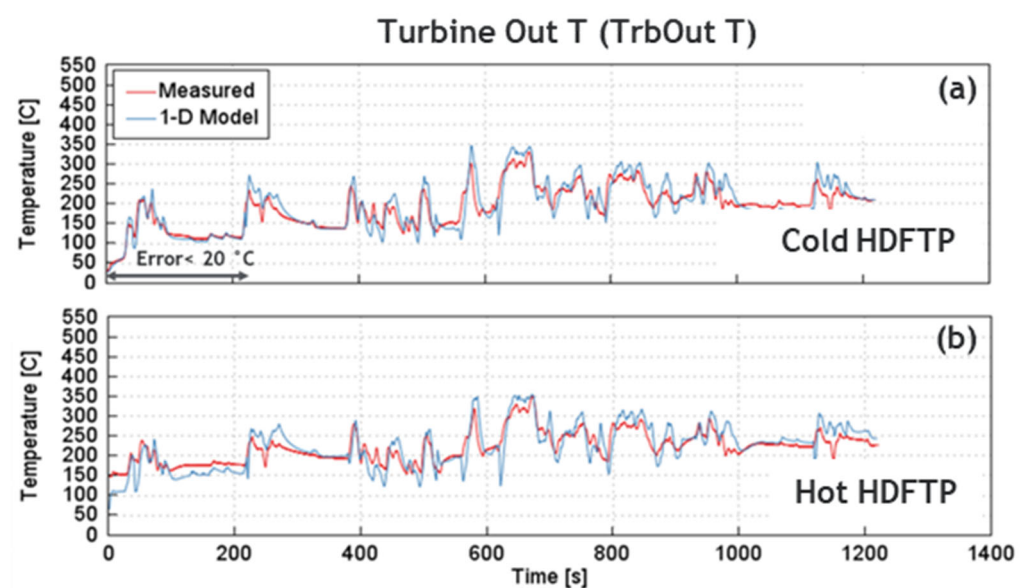


Figure 4. Correlation of turbine-out temperature prediction with measurements for (a) cold and (b) hot HDFTP cycles.

2.3. Electric Heater Component (EHC) Modeling

For EHC modeling, a production electric heater with a rating of up to 10 kW was procured and tested over the cold HDFTP cycle. Figure 5a,b show the EHC cross-section and an integrated dual-stage EHC with the stock ATS assembly, respectively. Subsequently, a 1-D catalyst monolith template in GT-Suite (implemented as a mesh-like structure with geometric dimensions) was used. The specific heat of the material and the convective heat transfer coefficient were calibrated using measurements. Figure 6 illustrates the DOC (diesel oxidation catalyst) temperature traces for the stock ATS and the EHC-integrated ATS configuration (Figure 5b). From Figure 6, the stock EHC significantly accelerated the DOC warm-up process, achieving the 200 °C threshold limit within the first ~120 s, compared to the no EHC case (solid lines). Both trends were quantitatively captured by the 1-D models with and without the EHC, as observed in Figure 6.

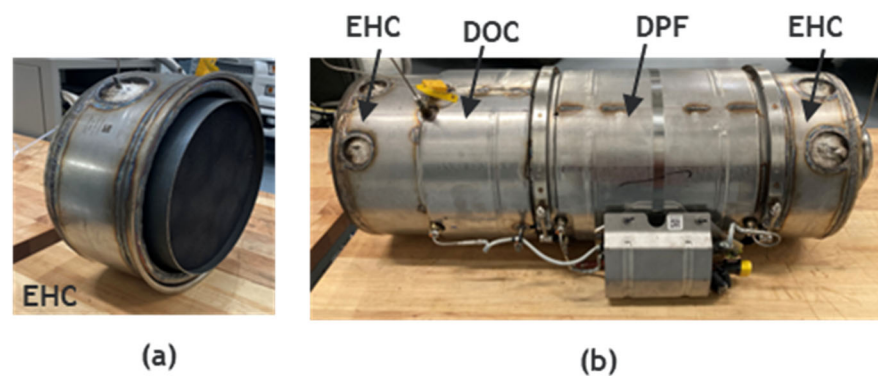


Figure 5. (a) The e-heater cross-section and (b) in-house packaged “EHC integrated ATS” system.

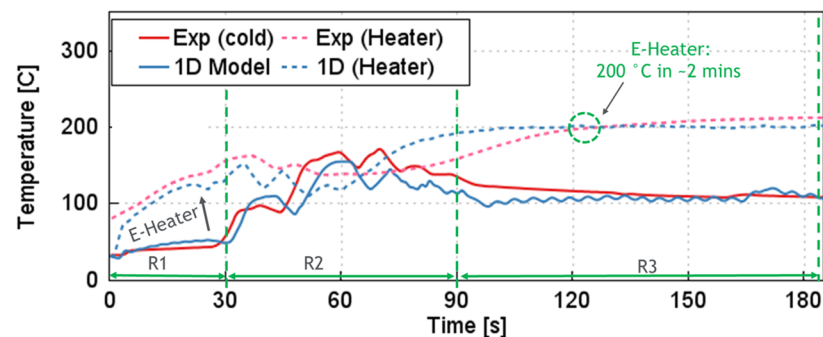


Figure 6. Measured and predicted response of 1-D EHC model (dash line) and stock ATS (solid line) for DOC temperature over the cold HDFTP cycle.

2.4. Real-World Driving Cycles

To study the differences between certification cycles and real-world long-haul driving for heavy-duty (HD) trucks, we examined the world harmonized vehicle cycle (WHVC) and real driving cycles across major global markets, including the US, Europe, India, and China. Using GT-RealDrive simulation software (V2022) [40], we generated vehicle speed profiles for busy trucking routes in each region.

Figure 7a–e show the speed profiles for the WHVC, as well as Chicago–San Francisco (Chi–San), Paris–Frankfurt (Par–Frkft), Mumbai–Chennai (Mum–Chen), and Beijing–Shanghai (Beij–Shng) routes, respectively. A summary of each cycle is the following:

1. World Harmonized Vehicle Cycle (WHVC):

- Duration of 1800 s, with an average speed of less than 40 km/h.
- A mix of idle, transient (urban driving), and highway cruising.
- Represents a certification cycle applicable globally but may not fully reflect real-world conditions.

2. Chicago–San Francisco (Chi–San) Route:
 - Duration of 36 h, with an average speed over 100 km/h.
 - Dominated by highway cruising.
 - Reflects real-world long-haul driving in the US.
3. Paris–Frankfurt (Par–Frkft) Route:
 - A mix of urban and highway cruising.
 - An average speed maintained over 75 km/h.
 - Represents European driving conditions.
4. Mumbai–Chennai (Mum–Chen) Route:
 - Dominated by transient behavior throughout the cycle.
 - A moderate average speed of nearly 50 km/h.
 - Reflects real-world driving patterns in India.
5. Beijing–Shanghai (Beij–Shng) Route:
 - Aggressive transients at both ends, indicating near port region driving.
 - The middle region maintains highway cruising above 100 km/h.
 - Represents real-world driving conditions in China.

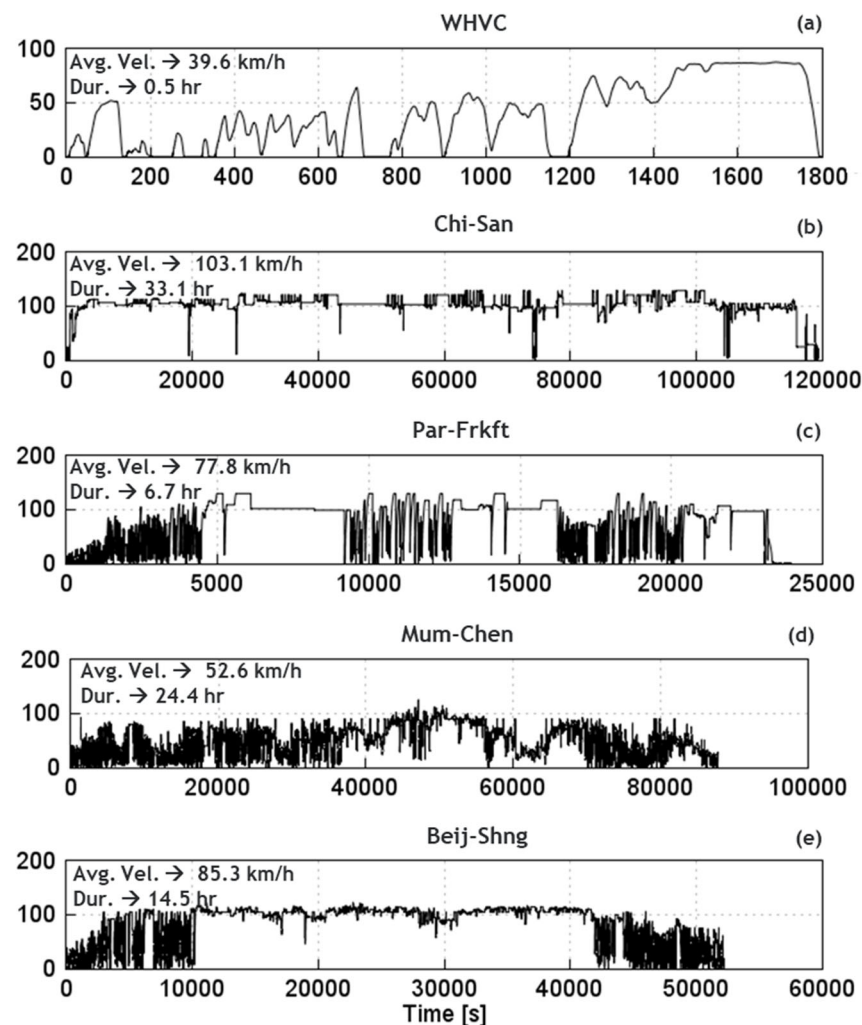


Figure 7. Simulated (a) WHVC and real driving cycles for (b) Chicago–San Francisco (Chi–San), (c) Paris–Frankfurt (Par–Frkft), (d) Mumbai–Chennai (Mum–Chen), and (e) Beijing–Shanghai (Beij–Shng) routes.

The differences in the vehicle speed, a mix of modes, and cycle duration significantly affected the engine's operation during real-world driving.

3. Objectives

Using the 1-D model, the performance of the four powertrains, including the (a) engine (non-hybrid), (b) P1 (mild-hybrid and stock ATS), (c) P1-ATS1 (mild-hybrid and single EHC integrated ATS configuration) and (d) P1-ATS2 (mild-hybrid and two EHCs integrated with ATS configuration), shown in Figures 8a, 8b, 8c and 8d, respectively, were evaluated.

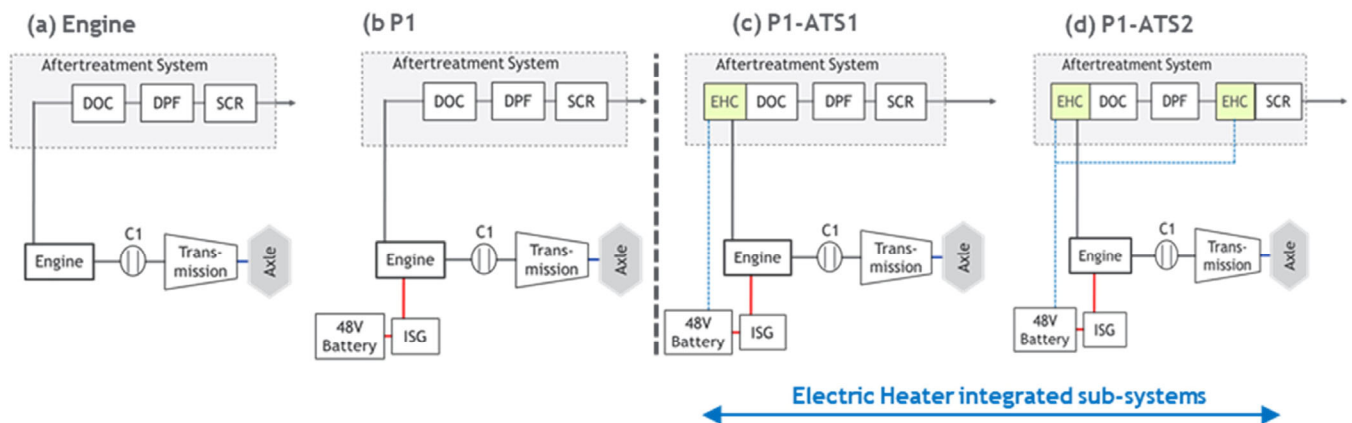


Figure 8. Schematic of powertrains, including (a) engine-only, (b) P1 mild-hybrid, (c) P1 with DOC-EHC, and (d) P1 with DOC-EHC and SCR-EHC.

From the selected powertrains (Figure 8), five different vehicle configurations were conceptualized based on the propulsion, calibrations, and ATS combinations. Table 5 shows the vehicle configurations. Over each driving cycle, first, the ‘Engine’ powertrain was evaluated using the High-NOx engine (‘Base’) in terms of the cumulative engine-out NOx levels, the net cumulative fuel consumption (net FC), the DOC mid-bed temperature (DOC-Bed), and the SCR mid-bed temperature (SCR-Bed), serving as a reference. Subsequently, the effects of the Low-NOx engine were quantified over the reference. Later, hybrid powertrains, including the P1, P1-ATS1, and P1-ATS2, were analyzed for their potential benefits in the cumulative engine-out NOx, net FC, DOC-Bed, and SCR-Bed levels. For the powertrains, including the EHC-integrated ATS, cycle-averaged catalyst bed warm-up time reduction vs. additional fuel consumption (FC) via EHC power consumption was reported for a value proposition assessment. From literature [17], the net cumulative fuel consumption (net FC) was estimated as follows:

$$\text{net FC(g)} = \text{Cumulative engine fueling(g)} \pm (\text{SOC}_{\text{end}} - \text{SOC}_{\text{init}}) \times \text{Battery Capacity(kWh)} \times \text{BSFC}_{\text{cycle-avg}} \left(\frac{\text{g}}{\text{kWh}} \right). \quad (1)$$

Table 5. Five vehicle configurations involving propulsion, calibration, and ATS.

VehicleConfigs. →	High-NOx (‘Base’)	Low-NOx	P1	P1-ATS1	P1-ATS2
Propulsion	Engine-Only	“	Hybrid	“	“
Calibration	High-NOx	Low-NOx	“	“	“
ATS	Stock	Stock	Stock	DOC-EHC(ATS1)	DOC-EHC and SCR-EHC(ATS2)

ATS1 → EHC integrated at DOC inlet for the stock ATS configuration. ATS2 → EHCs integrated at DOC and SCR inlets for the stock ATS configuration.

All simulations were conducted at an ambient temperature level of 25 °C. For the ambient operations, separate engine cold-start calibration tables were implemented that switched to the standard calibration tables based on an estimated fueling energy threshold of 96.6 MJ. The threshold was estimated by monitoring the engine oil temperature threshold of 60 °C during the cold HDFTP cycle testing, as shown in Figure A1 in Appendix A.

4. Results

In this section, performances of five different vehicle configurations (Table 5) are discussed progressively in terms of the net FC, DOC-Bed, and SCR-Bed for each driving cycle. Later, the EHC power consumption impact on the net FC levels was quantified.

4.1. World Harmonized Vehicle Cycle (WHVC)

Figure 9a–d illustrate the DOC-Bed and SCR-Bed temperatures, battery state-of-charge (SOC), and battery power flow traces (including the EHC and ISG loads), respectively, for the five vehicle configurations during the WHVC. In the High-NO_x ('Base') configuration, both DOC-Bed and SCR-Bed reached the 200 °C threshold within the first 120 s and 600 s, respectively. However, due to degraded exhaust enthalpy, the Low-NO_x configuration nearly doubled the warm-up time for both DOC and SCR. Interestingly, P1 (electrification) had no significant impact on the DOC and SCR thermal responses (Figure 9a,b), but it facilitated regenerative braking energy recovery, as evident from the SOC trends and frequent charging events in Figures 9c and 9d, respectively. Integrating the electric heater component (EHC) with the stock ATS significantly improved the catalyst's thermal response. In the P1-ATS1 configuration, the DOC-bed heated up rapidly (Figure 9a), while the P1-ATS2 configuration (using two EHCs) dramatically shortened the SCR warm-up time through extended EHC operation (Figure 9b). The impact of the EHC power consumption was evident from the SOC deterioration and frequent battery discharging due to EHC activity (Figure 9c,d), as expected.

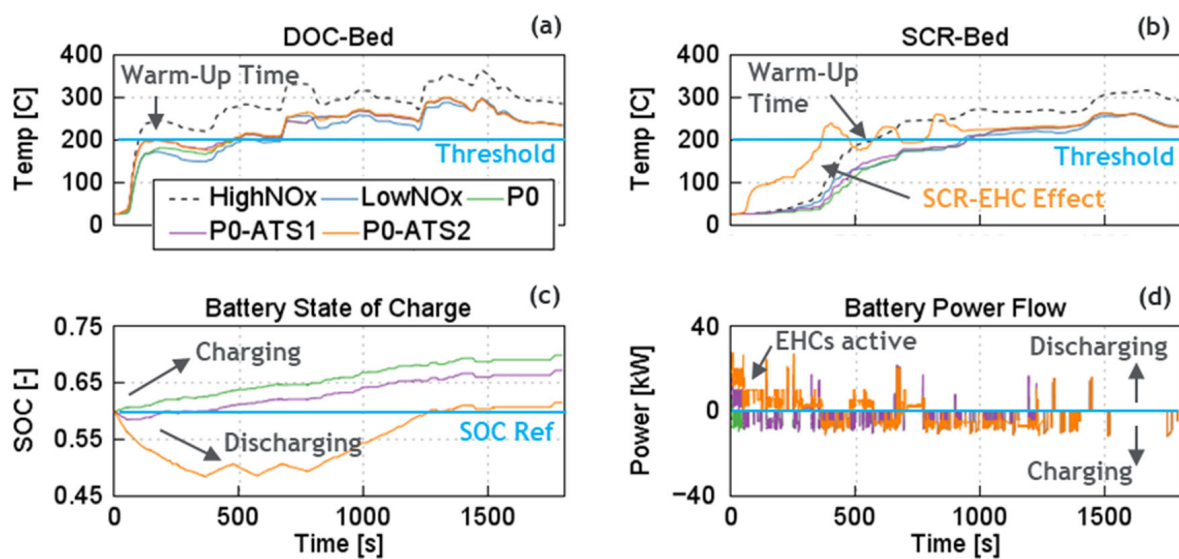


Figure 9. Comparison of (a) DOC-Bed temperature, (b) SCR-Bed temperature, (c) battery SOC, and (d) battery terminal power flow among the five powertrain configurations for WHVC.

In Figure 10a,b, the net cumulative fuel consumption (FC), DOC warm-up time (DOCwmup), and SCR warm-up time (SCRwmup), respectively, were analyzed among the five vehicle configurations over the WHVC driving profile. Compared to the 'Base,' the Low-NO_x configuration incurred a 4.1% FC penalty and doubled the catalyst warm-up time. However, P1 showed a 5.5% FC benefit (Figure 10a) with minimal impact on the ATS warm-up time (Figure 10b). Interestingly, in the P1-ATS1 configuration (EHC activity < 180 s), the DOCwmup decreased while maintaining a 5% FC benefit. Meanwhile, P1-ATS2 (two EHCs) achieved a warm-up time equivalent to the 'Base' (Figure 10b) but had an additional 1.3% FC penalty (Figure 10a) compared to Low-NO_x. The simulated integrated starter generator (ISG) and battery pack fully recovered regenerative braking energy during the WHVC.

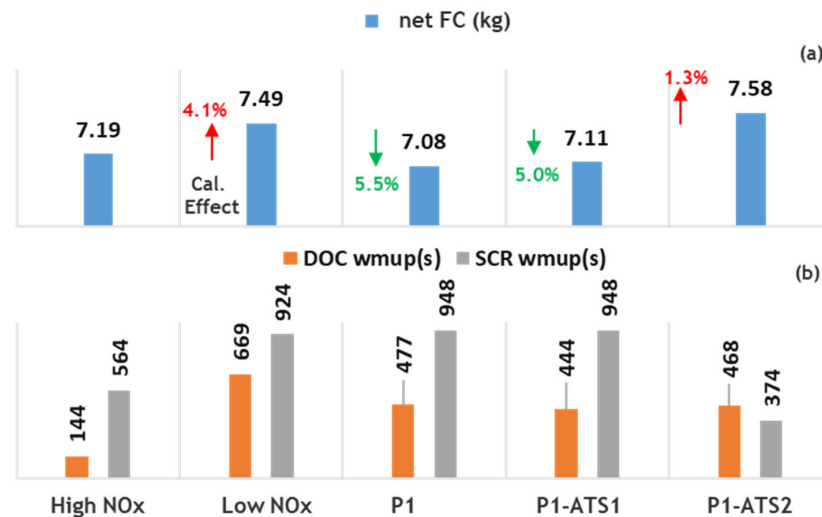


Figure 10. (a) Net cumulative fuel consumption (Net FC); (b) DOC and SCR catalysts warm-up time comparison among the five configurations for the WHVC.

4.2. Chicago–SanFrancisco (Chi–San)

In the high-load-demanding driving route for Chi–San, the ‘Base’ configuration resulted in cycle-averaged DOC and SCR temperatures exceeding 300 °C. For the Chi–San real driving cycle, traces of the DOC-Bed, SCR-Bed, battery SOC, and battery power flow were compared in Figures 11a, 11b, 11c and 11d, respectively, for the first 3600 s—the duration that mattered most for the ATS warm-up on the route. In Figure 11a,b, it is evident that the use of the Low-NOx configuration significantly delayed the catalyst responses, especially for the SCR system (Figure 11b), when compared to the ‘Base’ configuration. On the other hand, the P1 configuration had a negligible impact on the ATS thermal responses but enabled favorable SOC recovery (Figure 11c) from regenerative braking. This recovery was observed from the negative battery power flow traces in Figure 11d. Additionally, the use of the P1-ATS1 and P1-ATS2 powertrains showed noticeable thermal response improvements during the warm-up period. However, for the EHC operation, proportional system power was traded (20 kW for P1-ATS2, as seen in Figure 11d), leading to rapid battery SOC depletion (Figure 11c) during the first hour.

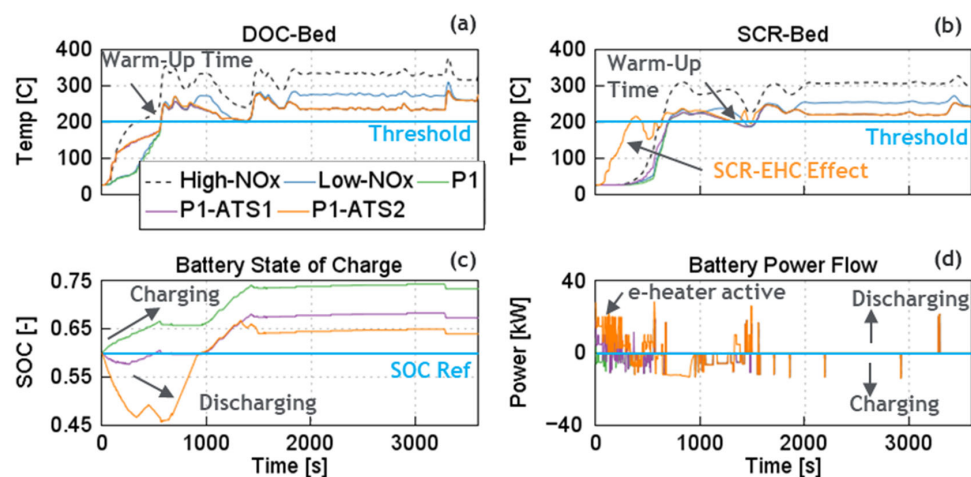


Figure 11. Comparison of (a) DOC-Bed temperature, (b) SCR-Bed temperature, (c) battery SOC, and (d) battery terminal power flow among the five powertrain configurations for the first hour of the Chi–San real driving cycle.

In Figure 12a,b, the net FC, DOC warm-up, and SCR warm-up were compared for the five vehicle configurations (refer to Table 5) over the complete Chi–San real driving

cycle. Initially, the Low-NOx configuration resulted in a 2.7% net FC increase (Figure 12a) along with a nearly three times longer SCR warm-up duration (Figure 12b) compared to the ‘Base’ configuration. The P1 configuration, with a negligible thermal impact, showed marginal (0.02%) net FC benefits, primarily due to the fewer regen braking events that were only observed during the first and last hours of the Chi–San route (less than 10% of the cycle duration). The use of EHC during the first 3600 s naturally aided ATS warm-up but inherently led to higher net FC levels due to fewer regen events. For the P1-ATS2 configuration, nearly 2.8% (~27 kg) of additional fueling was required to achieve similar DOC and SCR warm-up times as the ‘Base’ levels (Figures 12a and 12b, respectively). While a stronger hybridization may reduce FC differences, it presented an unfavorable cost-to-benefit trade-off, given the dominant highway cruising nature of the Chi–San route.

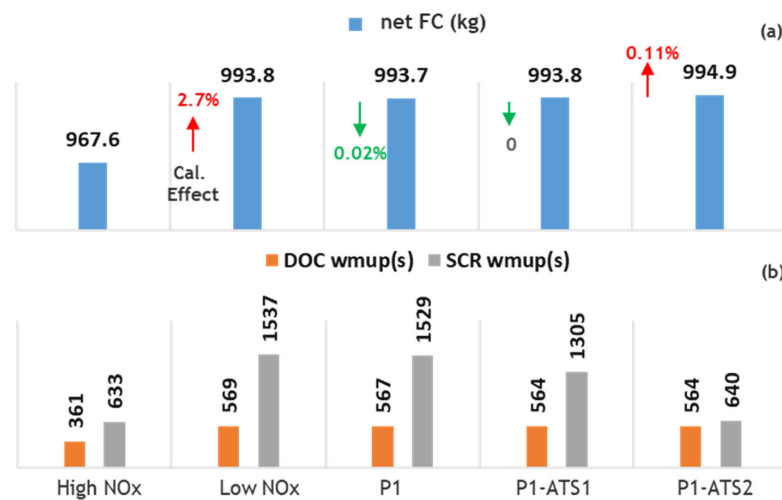


Figure 12. (a) Fuel consumption; (b) DOC and SCR catalysts warm-up time comparison among the five powertrain configurations for the Chi–San driving cycle.

4.3. Paris–Frankfurt (Par–Frkft)

For the Par–Frkft route, Figure 13a–d compared the DOC-Bed temperature, SCR-Bed temperature, SOC, and the battery terminal power trends during the first 3600 s, respectively, for the five vehicle configurations. Initially, for this route, the cycle-averaged catalyst temperatures were noted to be 50 °C higher than the US route (refer to Figure 11). This difference was partly attributed to urban-like transients that pushed engine operations near high loads during accelerations, resulting in elevated exhaust temperature levels.

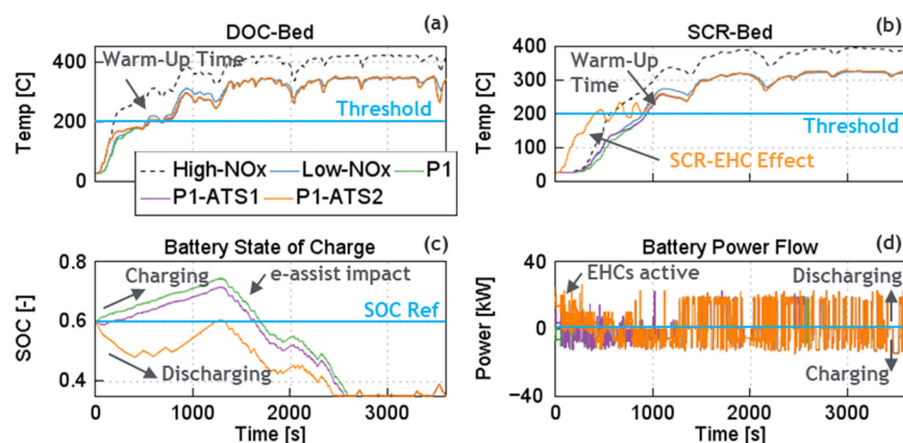


Figure 13. Comparison of (a) DOC-Bed temp, (b) SCR-Bed temp, (c) battery SOC, and (d) battery terminal power flow among the five powertrain configurations for the first hour of the Par–Frkft driving cycle.

In Figure 13a,b, it is evident that the Low-NOx configuration further delayed the catalysts' thermal response by several hundred seconds due to degraded exhaust enthalpy, as expected. Using the P1 configuration, catalyst warm-up was affected during the initial transients due to frequent engine-off events. The battery SOC (Figure 13c) and battery power (Figure 13d) trends responded to regenerative braking and dominant e-assist events (as shown in Figure 13d), leading to rapid SOC depletion (with a minimum SOC level of 0.35) within the first 3600 s. As anticipated, using two EHCs for ATS (P1-ATS2) proved more effective than a single EHC (P1-ATS1) with proportionally increased heater power consumption. However, for P1-ATS2, the instantaneous battery SOC and battery terminal power traces (Figures 13c and 13d, respectively) indicated rapid SOC depletion due to both EHCs' activity and subsequent e-assist for the P1-ATS2 configuration. Evidently, due to high EHC parasitic losses, frequent e-assist, and fewer regen braking events, powertrain system efficiency was expected to decrease.

For the Par-Frkft cycle, the net FC and warm-up times of the DOC and the SCR catalysts were compared among five vehicle configurations from Figures 14a and 14b, respectively. Initially, from the 'Base' level, the Low-NOx configuration showed approximately a 4.5% increase in net FC (Figure 14a) and several hundred seconds of delayed DOC and SCR warm-up times (Figure 14b). The use of P1 barely displayed a fueling benefit and further extended both catalysts' heating time by ~100 s (Figure 14b). EHC usage further increased the fuel consumption levels. For the P1-ATS2 configuration, two EHCs' activity, e-assist, and fewer braking energy recovery combined led to an additional 4.5% FC compared to the Low-NOx configuration. Throughout the cycle, this resulted in ~21 kg of extra fueling over the 'Base' level. It can be conjectured that a stronger hybridization would be desirable to neutralize EHC power usage and minimize net FC.

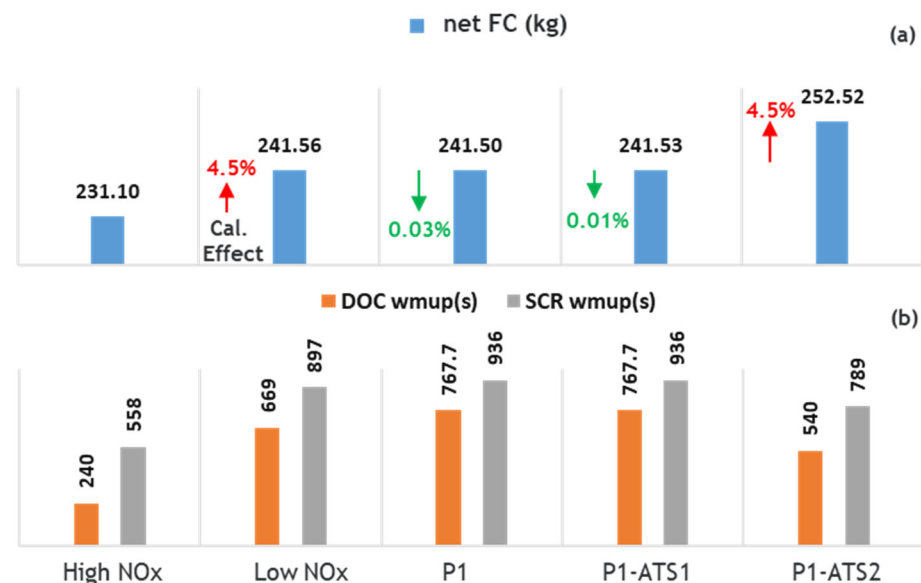


Figure 14. (a) Fuel consumption; (b) DOC and SCR catalysts warm-up time comparison among the five powertrain configurations for the Par-Frkft driving cycle.

4.4. Mumbai–Chennai (Mum–Chen)

In the Mum–Chen driving cycle, characterized by an average vehicle speed of approximately 53 km/h, the engine operated at an average brake mean effective pressure (BMEP) of 5.5 bar, resulting in catalyst temperatures of around 250 °C for the 'Base' configuration. These temperatures were significantly lower than those observed in western trucking routes. Figure 15a–d compare the DOC-Bed, SCR-Bed temperatures, battery SOC, and battery power trends, respectively, among the five vehicle configurations during the initial 3600 s.

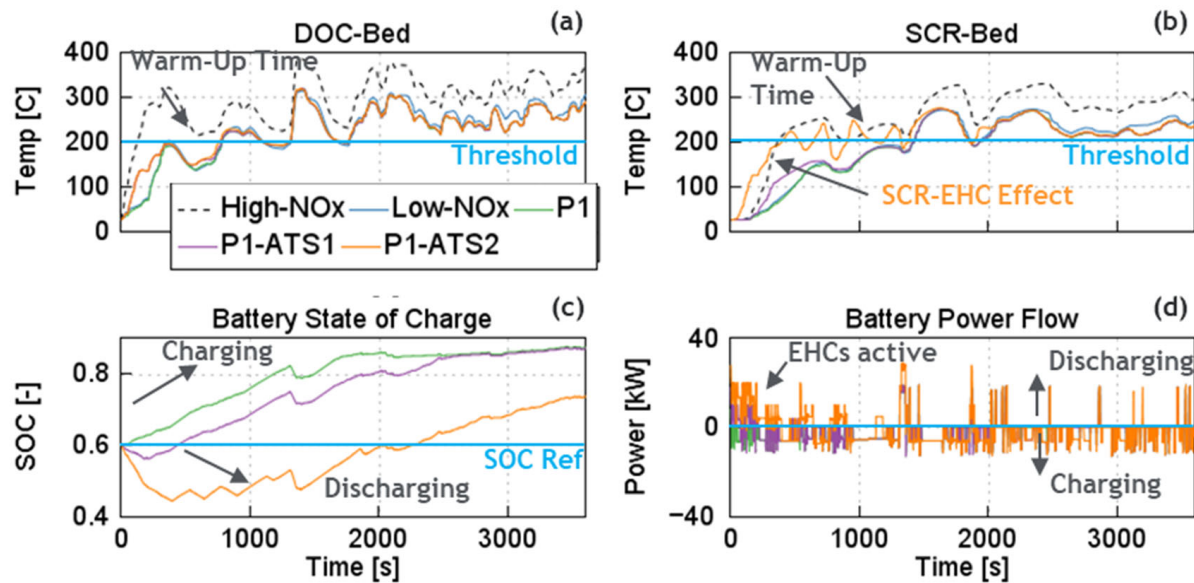


Figure 15. Comparison of (a) DOC-bed temp, (b) SCR-bed temp, (c) battery SOC, and (d) battery terminal power flow among the five powertrain configurations for the first hour of the Mum–Chen driving cycle.

The Low-NOx configuration notably delayed the warm-up times for both the DOC-Bed (Figure 15a) and the SCR-Bed (Figure 15b). Leveraging transient events during the cycle, the P1 configuration demonstrated an improved battery SOC (as shown in Figure 15c) through frequent regenerative braking events (Figure 15d). Notably, the cycle-averaged SCR-Bed temperature remained below the desirable 200 °C level. Electrically heated catalysts (EHC), warranted for elevating catalyst temperatures, showed a faster DOC thermal response when integrated with the stock ATS (P1-ATS1) over this cycle, as seen in Figure 15a. Impressively, the P1-ATS2 configuration enabled the shortest SCR warm-up time among the five vehicle configurations. In Figure 15d, the two EHCs' power consumption led to a severe SOC depletion, initially, for P1-ATS2 (as shown in Figure 15d). Subsequent regenerative braking events during the later portion of the cycle successfully recovered the SOC levels, as noted in Figure 15c.

Over the complete Mum–Chen driving route, the net FC and catalysts' (DOC and SCR) warm-up times were compared for the five vehicle configurations in Figures 16a and 16b, respectively. The Low-NOx configuration resulted in a 0.9% FC penalty (Figure 16a) and caused several times higher catalysts' warm-up times (Figure 16b). While P1 improved net FC by approximately 0.5%, P1-ATS1 showed similar benefits due to limited e-heater usage (during the first 300 s), resulting in a heating pattern similar to that of the P1 configuration. The most favorable EHC performance was observed for P1-ATS2, which markedly reduced the SCR warm-up time by ~50% (Figure 16b) at an additional 0.5% fueling increase (from Figure 16a), compared to the Low-NOx vehicle configuration.

It was expected that a higher power rating and prolonged EHC usage would significantly elevate both the DOC and SCR thermal responses, provided adequate regenerative braking was harnessed to neutralize the EHC power consumption during vehicle operation. Figure 17 shows the instantaneous available and actual regenerative braking power traces for the Mum–Chen driving route. Interestingly, substantial portions of available braking energy during the initial and final segments of the cycle (as depicted in Figure 17) remained unrecovered due to the limitations imposed by the integrated starter generator (ISG) power rating. Consequently, achieving rapid heating while minimizing fuel consumption demands a stronger hybridization characterized by a high motor rating coupled with high EHC ratings for the Mum–Chen real driving cycle.

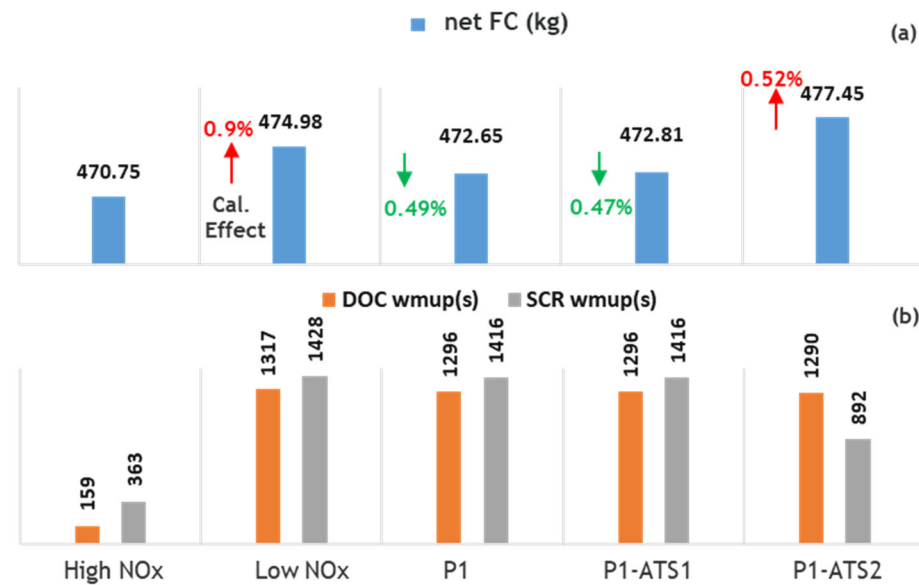


Figure 16. (a) Fuel consumption; (b) DOC and SCR catalysts warm-up time comparison among the 5 powertrain configurations for the Mum–Chen driving cycle.

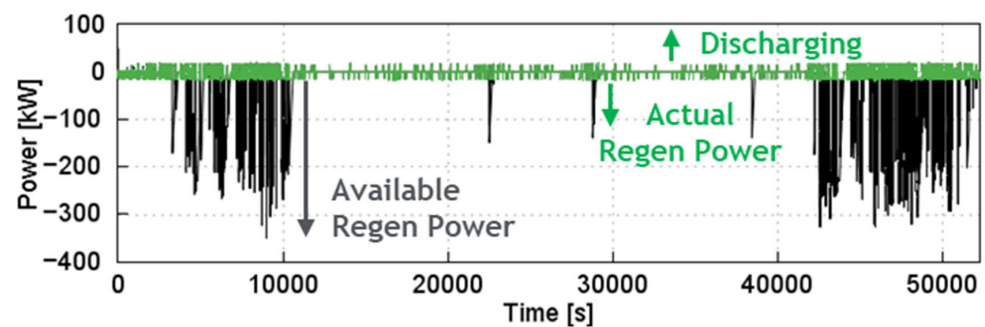


Figure 17. Traces of available power and actual ISG power compared using P1 for the Mum–Chen driving cycle.

4.5. Beijing–Shanghai (Beij–Shng)

The Beijing–Shanghai (Beij–Shng) real driving cycle comprised the most aggressive transients among the five cycles and exhibited an average vehicle speed of 85 km/h (refer to Figure 7e). This high vehicle speed demand led to an average BMEP level similar to that of the US counterpart. Furthermore, Figure 18a–d compared the temperatures of the diesel oxidation catalyst (DOC-Bed), selective catalytic reduction (SCR-Bed), battery state-of-charge (SOC), and battery power trends, respectively, among the five vehicle configurations during the initial 3600 s. In the ‘Base’ configuration, which maintained average aftertreatment system (ATS) temperatures well above 300 °C, both the DOC-Bed (Figure 18a) and SCR-Bed (Figure 18b) temperatures were significantly affected for the Low-NOx configuration. When using P1, the battery SOC improved initially, followed by a rapid decline, as seen in Figure 18c. This was primarily attributed to frequent energy assist events during acceleration, as verified by the battery terminal power traces shown in Figure 18d. For the P1-ATS1 configuration, the DOC-Bed temperature improved, while the P1-ATS2 configuration exhibited significant ATS warm-up benefits, particularly for the SCR-Bed (Figure 18b). These configurations had proportional effects on the battery SOC and the instantaneous battery terminal power associated with electric heating circuits (EHCs). The use of two EHCs for P1-ATS2 caused a rapid SOC depletion that recovered during the regen braking events.

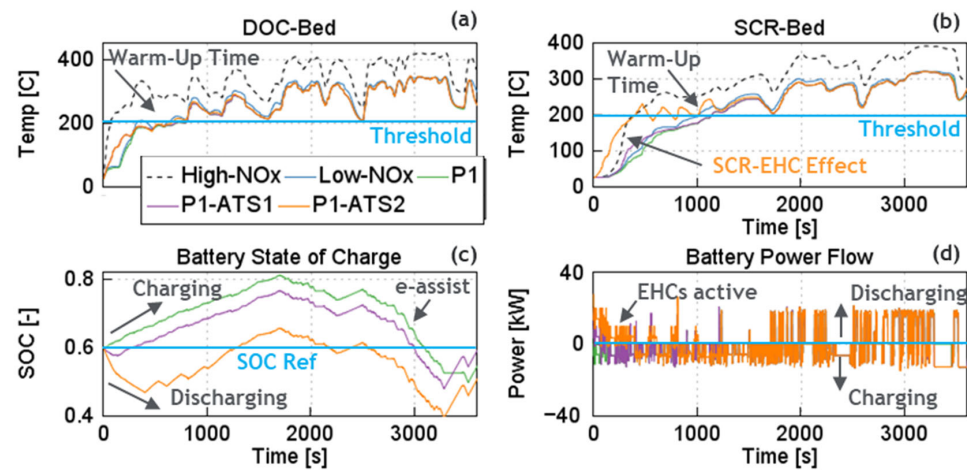


Figure 18. Comparison of (a) DOC-Bed temp, (b) SCR-Bed temp, (c) battery SOC, and (d) battery terminal power flow among the five powertrain configurations for the first hour of the Beij-Shng driving cycle.

Figure 19a,b show the cumulative net fuel consumption and the estimated catalyst warm-up time, respectively, among the five vehicle configurations: a 1.3% higher net FC and a 3–4 times higher catalyst warm-up time for the Low-NOx configuration. Interestingly, the P1 configuration noted an additional 0.95% fuel consumption. This was caused due to inadequate regen events due to a limited ISG rating. Expectedly, the usage of EHCs further increased the fueling penalty. For the P1-ATS2 configuration, an additional 1.1% (~11 kg) net FC was observed over 'Low NOx' while achieving similar DOC and SCR warm-up times. For P1-ATS2 to achieve satisfactory results, larger ISG power ratings would be desirable, incurring further fueling penalties.

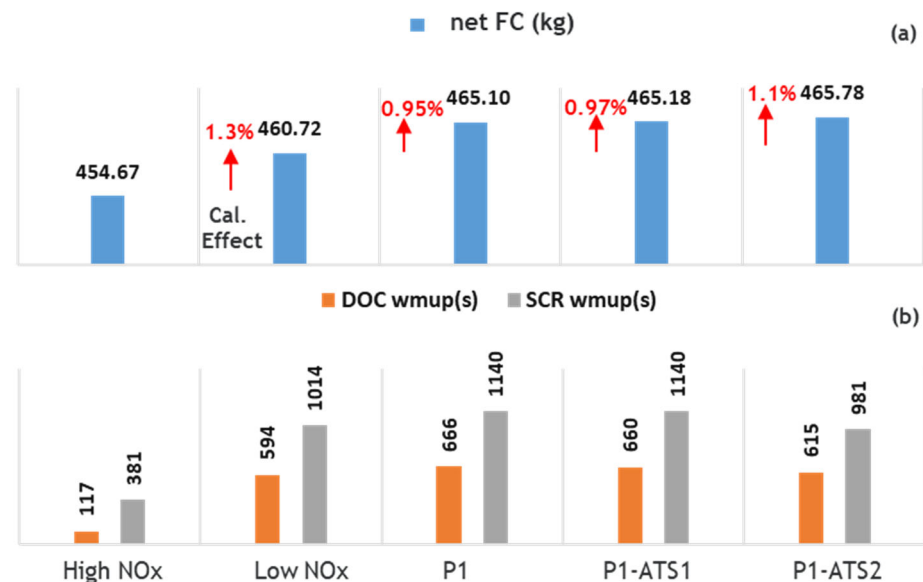


Figure 19. (a) Fuel consumption; (b) DOC and SCR catalysts warm-up time comparison among the 5 powertrain configurations for the Beij-Shng driving cycle.

Furthermore, to understand the details of P1's inadvertent result of an increased FC (as noted in Figure 19a) over the Beij-Shng route, cumulative fueling traces for P1 and Low-NOx were plotted in Figure 20. The combined impact of increased engine operations near its peak levels (reduced thermal efficiency region), frequent e-assists (transients during the urban regions), and inadequate regenerative braking from the stock ISG rating resulted

in a large net fuel consumption over the cycle; however, high fueling was a requirement, despite this.

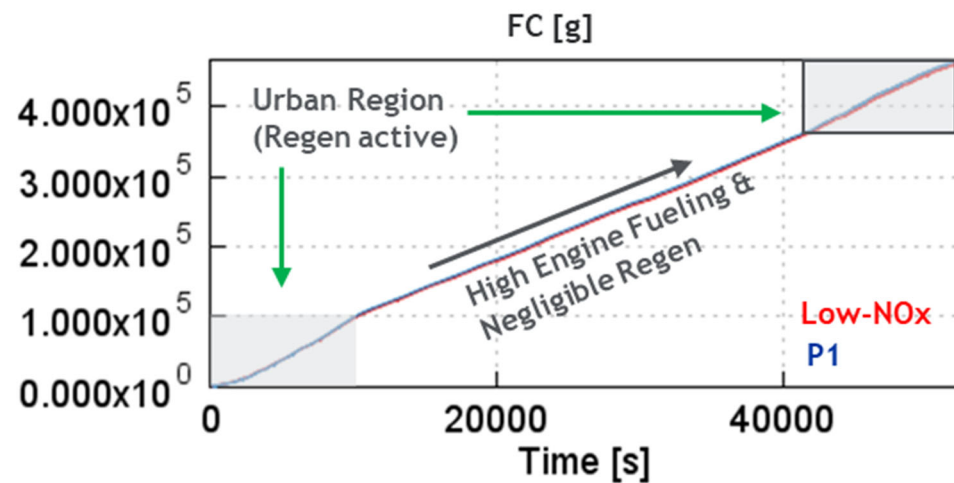


Figure 20. Cumulative fuel consumption (FC) trends comparison between the Low-NOx and P1 configurations over the Beij-Shng driving cycle.

For the Beij-Shng route, although the P1-ATS2 configuration effectively addressed the DOC and the SCR warm-up challenges, ineffective regenerative braking appeared as a major hurdle to its practicality. To analyze the opportunities for regen braking events in this cycle, instantaneous traces of available and actual regenerative braking energy were compared, in Figure 21. It was confirmed that large regenerative braking power pools (over 300 kW) were available in the urban regions. However, the limited 20 kW ISG rating failed to recover most of it, like the Indian counterpart. A stronger hybridization would be desirable for this driving route.

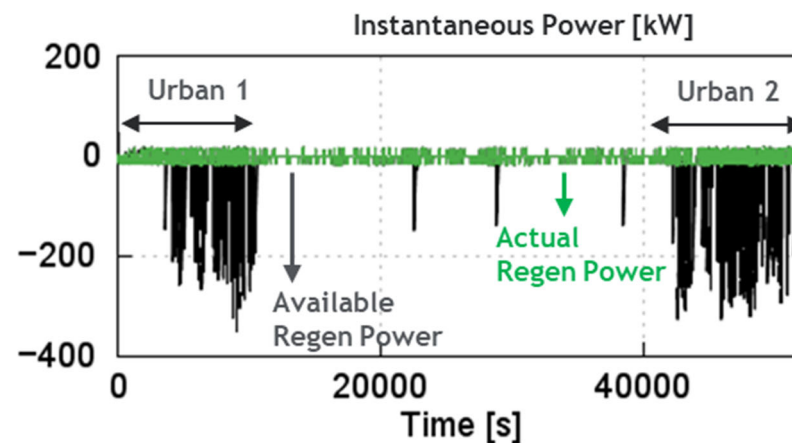


Figure 21. Traces of available power and actual ISG power using P1 for the Beij-Shng driving cycle.

4.6. NOx and FC Trade-Offs

From the observed performances over different driving routes (previous sections), the use of a Low-NOx engine configuration, despite some implications on the initial ATS warm-up and fuel consumption, shows large engine-out NOx emissions reductions. The use of the 'Low-NOx' engine for 48V hybridization would be practical in the near term due to its high potential to meet the 2027 NOx 0.02 g/kWh emissions compliance [25,33]. Assessment of the benefits of NOx emissions and the fuel consumption of such powertrains, compared to the 'Base', over the real driving routes, would be of high importance for the engine manufacturers. To that end, Figure 22 compares the cumulative NOx emissions and the net FC trade-off trends (normalized scales) for the 'Low-NOx' and the P1-ATS2 vehicle

configurations. Over different driving cycles, the use of the Low-NOx vehicle configuration alone showed a 70–80% reduction in NOx emissions consistently, which subsequently was maintained for the P1-ATS2 configuration. From the fueling level trends in Figure 22, the 1–3% fueling penalty range observed in Asian markets could be mitigated through a stronger hybridization, as previously discussed. Interestingly, the Paris–Frkft route, which involves large e-assist events, exhibited a ~9% penalty for P1-ATS2. However, this penalty can be partially offset by adopting a more robust hybrid system.

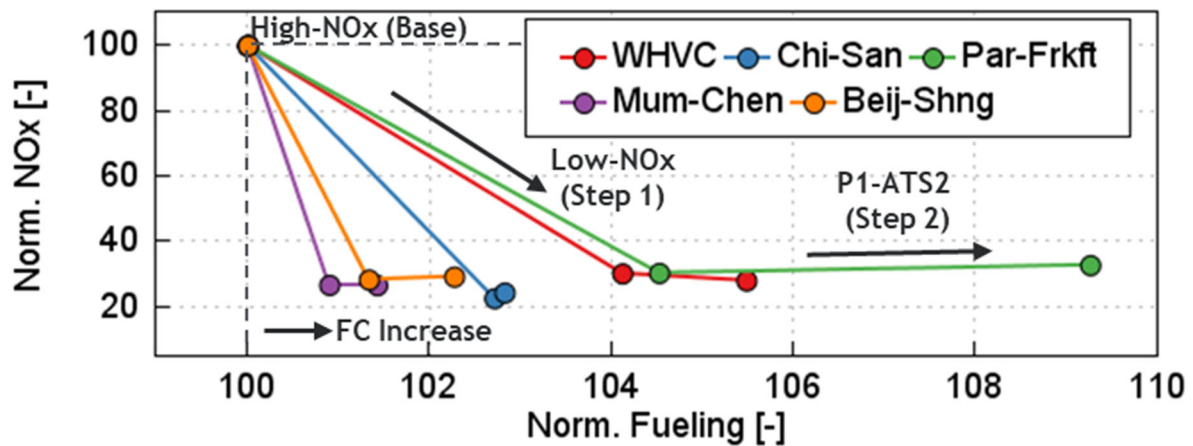


Figure 22. The trade-off of normalized cumulative NOx vs. cumulative fueling for the five drive cycles.

To gauge the value proposition of EHCs in hybrid vehicle configurations, the ratio of the observed warm-up time reduction benefit, with respect to the increased fuel consumption, is important. To that end, the increased net FC (g), with respect to the reduction in selective catalytic reduction (SCR) warm-up time (s) via EHCs, referred to as FC_{EHC} (g/s), was estimated for the P1-ATS2 configuration over the five real driving cycles, as shown in Figure 23. Notably, the low FC_{EHC} levels for the WHVC cycle indicated the high effectiveness of the P1-ATS2 configuration in offsetting the EHC power consumption. In contrast, for the real-world driving cycles, the FC_{EHC} values were significantly higher. For the Chi-San and Par-Frkft routes, the combination of EHC usage, fewer regenerative braking events, e-assists, and predominant highway cruising resulted in the 2 to 3.7 FC_{EHC} range. Expectedly, the India and the China routes, despite a large number of transient events, exhibited FC_{EHC} levels well over 4 g/s. A stronger hybridization for India and China (by allowing increased regenerative braking) would be imperative so as to mitigate high FC_{EHC} levels.

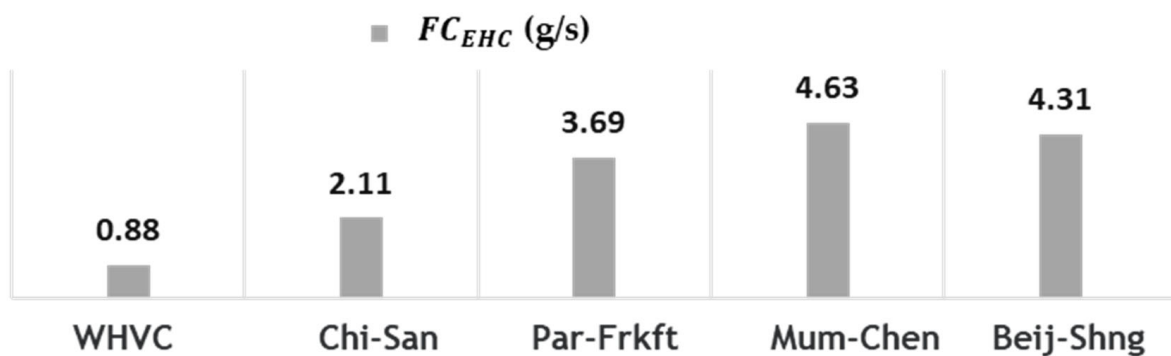


Figure 23. The ratio of additional fuel consumption to the SCR warm-up time reduction using P1-ATS2 relative to the P1 for the five drive cycles.

5. Conclusions

In the present work, a 48V mild-hybrid class 8 commercial vehicle concept, based on an EPA-2010-certified stock ISX15 HD diesel engine, was evaluated over real-world driving cycles, including the US, Europe, India, and China and the world harmonized vehicle cycle (WHVC). The benefits of the 10 kW electric heater components (EHCs) system for an aftertreatment warm-up time reduction and P1 hybridization for GHG benefits were quantified over each cycle. First, switching the stock engine with a Low-NO_x engine concept demonstrated a 70–80% reduction in the engine-out NO_x emissions, 0.9–4.5% increased net fuel consumption (net FC), and 300–700 s increase in the DOC and SCR warm-up times, warranting electric heating.

Subsequently, the EHC-integrated ATS system in a P1 hybrid propulsion system reduced the ATS warm-up time via electric heating and the net fuel consumption (net FC) level via regenerative braking. The two EHCs (10 kW each) integrated into the ATS system were noted as the most effective for an accelerated ATS warm-up, with a slight increase in net FC. For the US and Europe routes, the increased net FC levels were primarily caused due to frequent e-assists and negligible regenerative braking, leading to a large SOC decline over the complete duration of the cycles. Interestingly, for the India and China routes, a ~4–5 times higher net FC was observed, largely due to an inadequate harnessing of the available regenerative braking energy, owing to the limited 20 kW ISG motor for P1. For such markets, a stronger hybrid appeared more desirable for a concurrent NO_x and CO₂ emissions reduction. Finally, the over-optimistic net FC levels over the WHVC cycle suggest that the 48V MHEV powertrain must be evaluated over real-world driving conditions for a minimized total operating cost.

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Nomenclature

ARB	Air Resources Board
ACT	Advanced Clean Trucks
BEV	Battery Electric Vehicle
BSFC	Brake Specific Fuel Consumption
CA50	Crank Angle for 50% Heat Release
CAD	Crank Angle Degrees
DC	Direct Current
DoE	Design of Experiments
DOC	Diesel Oxidation Catalyst
DOC _{wmup}	DOC Warm-up time
DPF	Diesel Particulate Filter

EGR	Exhaust Gas Recirculation
EHC	Electric Heater Component
EPA	Environmental Protection Agency
EV	Exhaust Valve
FC	Fuel Consumption
GHG	Greenhouse Gas
GR	Gear Ratio
GT	Gamma Technologies
GVWR	Gross Vehicle Weight Rating
HDFTP	Heavy Duty Federal Test Procedure
ICE	Internal Combustion Engine
IMEPg	Gross Indicated Mean Effective Pressure
IMEPn	Net Indicated Mean Effective Pressure
ISG	Integrated Starter Generator
IV	Intake valve
MG	Motor Generator Unit
MHEV	Mild Hybrid Electric Vehicle
NM	Nickel Manganese Cobalt Oxide Li-Ion Battery
OCV	Open Circuit Voltage
PMEP	Pumping Mean Effective Pressure
SCR	Selective Catalytic Reaction
SCRwmup	SCR Warm-up Time
SOC	State of Charge
SOC _{end}	Battery State of Charge at the end of the drive cycle
SOC _{init}	State of Charge at the beginning of the drive cycle
SOI	Start of Injection
VNT	Variable Nozzle Turbine
ZEV	Zero Emission Vehicle

Appendix A

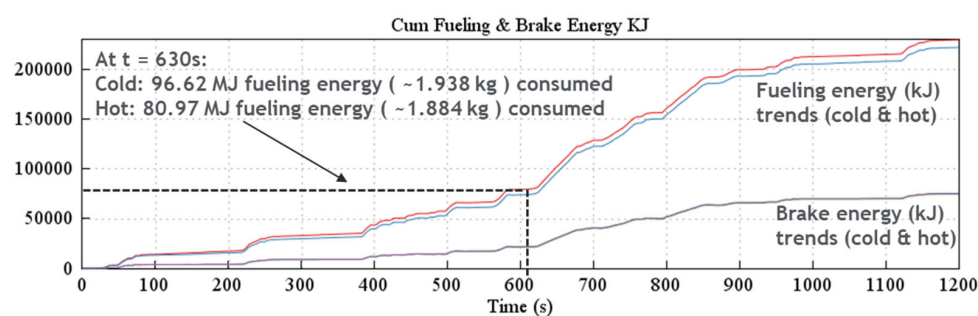


Figure A1. Cumulative fueling energy traces for the cold and hot HDFTP cycles.

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