

INFLUENCE OF ECU CALIBRATION ON BRAKE THERMAL EFFICIENCY, EXHAUST HEAT AVAILABILITY, AND ENGINE-OUT EMISSIONS IN A SPARK-IGNITION ENGINE

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Abstract

This study examines how Engine Control Unit (ECU) calibration parameters—ignition timing advance (ITA) and excess-air ratio (λ)—affect brake thermal efficiency (BTE), estimated exhaust heat availability (Q_{ex}), and engine-out emissions in a gasoline-fuelled spark-ignition engine. A four-cylinder, 1598 cm³, naturally aspirated engine equipped with a programmable Motec M130 ECU was tested using ITA settings of 20°, 24°, 28°, and 32° before top dead centre (BTDC), λ values of 0.9, 1.0, and 1.1, engine speeds of 1500–4000 rpm, and four load levels, yielding 288 steady-state operating conditions with three acquisitions per condition. Integrated comparisons were restricted to 3000 rpm at full load so that efficiency, thermal, and emission variables represented the same operating point. BTE peaked at 34.2% at 28° BTDC and $\lambda = 1.0$, representing a 9.6% relative increase over 20° BTDC. At 28° BTDC, Q_{ex} calculated from measured exhaust mass flow and exhaust-gas temperature was 31.1 kW at $\lambda = 0.9$, 26.3 kW at $\lambda = 1.0$, and 22.3 kW at $\lambda = 1.1$. Relative to stoichiometric operation, rich calibration increased CO by 131% and HC by 58%, whereas lean calibration reduced CO by 50% and NO_x by 17.9% but increased HC by 22.2%. Among the tested conditions at the common operating point, 28° BTDC and $\lambda = 1.0$ provided the best overall compromise, combining maximum BTE, minimum HC, and moderate exhaust thermal potential. The results represent steady-state engine-out behaviour and should not be interpreted as tailpipe emission compliance or directly recoverable waste-heat-recovery power.

Keywords:

Brake Thermal Efficiency; ECU Calibration; Engine-Out Emissions; Exhaust Heat Availability; Waste Heat Recovery.

Abstrak

Penelitian ini mengkaji pengaruh parameter kalibrasi Engine Control Unit (ECU), yaitu kemajuan waktu pengapian (ITA) dan rasio udara berlebih (λ), terhadap brake thermal efficiency (BTE), estimasi ketersediaan panas gas buang (Q_{ex}), dan emisi engine-out pada mesin bensin berpengapian bunga api. Mesin empat silinder berkapasitas 1598 cm³ yang dilengkapi ECU programmable Motec M130 diuji pada ITA 20°, 24°, 28°, dan 32° sebelum titik mati atas (BTDC), λ sebesar 0,9; 1,0; dan 1,1, putaran 1500–4000 rpm, serta empat tingkat beban. Matriks pengujian menghasilkan 288 kondisi tunak dengan tiga kali akuisisi pada setiap kondisi. Perbandingan terpadu dibatasi pada 3000 rpm dan beban penuh agar variabel efisiensi, termal, dan emisi berasal dari titik operasi yang sama. Nilai BTE tertinggi sebesar 34,2% diperoleh pada 28° BTDC dan $\lambda = 1,0$, atau meningkat 9,6% secara relatif dibandingkan 20° BTDC. Pada 28° BTDC, Q_{ex} yang dihitung dari laju aliran massa dan temperatur gas buang adalah 31,1 kW pada $\lambda = 0,9$, 26,3 kW pada $\lambda = 1,0$, dan 22,3 kW pada $\lambda = 1,1$. Dibandingkan kondisi stoikiometri, kalibrasi kaya meningkatkan CO sebesar 131% dan HC sebesar 58%, sedangkan kalibrasi miskin menurunkan CO sebesar 50% dan NO_x sebesar 17,9%, tetapi meningkatkan HC sebesar 22,2%. Di antara kondisi yang diuji pada titik operasi yang sama, 28° BTDC dan $\lambda = 1,0$ memberikan kompromi terbaik karena menghasilkan BTE maksimum, HC minimum, dan potensi termal gas buang yang moderat. Hasil penelitian ini merepresentasikan kondisi tunak engine-out dan tidak dapat langsung diartikan sebagai kepatuhan emisi tailpipe atau daya WHR yang benar-benar dapat dipulihkan.

Kata Kunci:

Efisiensi Termal Rem; Emisi Engine-Out; Kalibrasi ECU; Ketersediaan Panas Buang; Pemulihan Panas Buang.

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1. INTRODUCTION

The transportation sector remains a major consumer of primary energy and a significant source of combustion-related carbon dioxide emissions. Although vehicle electrification is accelerating, spark-ignition (SI) engines continue to be widely used in many passenger-vehicle markets, particularly where charging infrastructure and fleet turnover develop gradually (Heywood, 2018; IEA, 2024). Improving the thermal performance and engine-out emission characteristics of SI engines therefore remains an important engineering objective during the transition toward lower-carbon mobility.

The Engine Control Unit (ECU) is the primary interface through which engineers govern SI engine operational behaviour. Among the numerous parameters under ECU authority, ignition timing advance (ITA) and air-fuel ratio (AFR)—expressed as the excess air ratio (λ)—exert the most direct influence on in-cylinder combustion thermodynamics. ITA determines the crank angle at which spark discharge initiates flame kernel growth, profoundly affecting peak cylinder pressure, combustion phasing, and the resulting heat release profile (Pulkrabek, 2004). The AFR controls the stoichiometric balance of the oxidation reaction, governing combustion completeness, adiabatic flame temperature, and the production of regulated emission species including CO, HC, NO_x, and CO₂ (Stone, 2012).

From an energy balance perspective, SI engines typically convert only 30–40% of fuel chemical energy into crankshaft work, with the remainder dissipated through coolant heat rejection (~25–30%), exhaust gas enthalpy loss (~25–35%), and mechanical friction losses (~5–8%) (Heywood, 2018). The exhaust gas stream therefore represents the single largest recoverable thermal energy loss, with temperatures spanning 400°C to over 900°C across the operating range. Waste heat recovery (WHR) technologies—including organic Rankine cycle (ORC) systems, thermoelectric generators (TEGs), and turbocompounding—represent proven engineering pathways for improving vehicle fuel economy (Shu et al., 2018; Aghaali & Ångström, 2015; Saidur et al., 2012). Critically, the effectiveness of any WHR system is fundamentally governed by the temperature and mass flow rate of the exhaust supply, both of which are direct functions of ECU calibration parameters.

Previous experimental studies have generally examined these calibration effects one parameter and one response at a time. For ignition timing, Zareei and Kakaei (2013) reported that the brake torque and power of a gasoline engine at 3400 rpm and wide-open throttle peaked at 31° CA BTDC, and Ji et al. (2010) found that the maximum indicated thermal efficiency occurred at the optimum spark timing and declined as timing moved away from it. Both studies also showed that the efficiency benefit of advanced timing is accompanied by higher NO_x: NO_x was lowest at the most retarded setting (10° CA BTDC) in Zareei and Kakaei (2013) and decreased continuously with spark retard in Ji et al. (2010), consistent with the strong temperature dependence of thermal NO_x formation (Heywood, 2018). For mixture strength, CO and HC are controlled by oxygen availability, flame quenching, and crevice storage, so their response differs between rich and lean operation (Alkidas, 1999; Ji & Wang, 2009).

In parallel, WHR studies (Domingues et al., 2013; Wang et al., 2013) quantified how exhaust energy varies with engine speed and load, but did not vary the ECU calibration itself. As a result, brake efficiency, exhaust thermal availability, and multi-species engine-out emissions have rarely been measured together under controlled ITA– λ variation at a single speed-load point, and the trade-off between efficiency, emissions, and WHR potential that a calibration engineer faces remains unquantified. The present study addresses this gap through a controlled ECU-calibration campaign. The objectives are: (i) to quantify the effects of ITA and λ on BTE; (ii) to estimate exhaust heat availability from measured exhaust mass flow and temperature; (iii) to characterise CO, HC, NO_x, CO₂, and O₂ responses; and (iv) to identify a technically balanced calibration among the tested conditions without combining data from different speed-load points.

2. LITERATURE REVIEW

The effect of ITA on SI-engine performance and emissions is well established. Advancing the spark toward maximum brake torque (MBT) improves combustion phasing relative to top dead centre, increases the useful expansion work, and generally raises BTE. MBT timing is engine- and operating-condition-specific; when timing is advanced beyond MBT, negative compression work and wall heat transfer increase, causing efficiency to decline. Comparable non-monotonic responses have been reported for gasoline and blended-fuel SI engines (Ji et al., 2010; Karunanidhi et al., 2021; Tibola et al., 2016; Yildiz et al., 2022; Zareei & Kakaee, 2013). Zareei and Kakaee (2013) and Chen et al., (2019) also demonstrated that ignition timing strongly affects both brake torque and NOx formation in a gasoline engine.

NOx emission sensitivity to ITA is governed by the extended Zeldovich mechanism for thermal NOx formation, wherein reaction rates follow an Arrhenius relationship with peak in-cylinder temperature. Advanced ITA elevates peak combustion temperature, causing NOx formation rates to increase exponentially—an inherent trade-off against the efficiency benefit of MBT timing (Heywood, 2018; Ji et al., 2010). For WHR engineering, Wang et al. (2013) showed that exhaust heat availability varies significantly with engine speed and load, while Saidur et al. (2012) reviewed exhaust heat recovery technologies and emphasised that the recoverable energy depends on exhaust temperature and mass flow.

Mixture strength also governs combustion completeness and after-treatment compatibility. Stoichiometric operation ($\lambda = 1.0$) is required for a conventional three-way catalyst to treat CO, HC, and NOx simultaneously. Rich mixtures ($\lambda < 1.0$) increase CO and HC because oxygen is insufficient for complete oxidation. Lean mixtures ($\lambda > 1.0$) reduce flame temperature and may reduce NOx and CO, but can increase HC through slower oxidation, wall quenching, and partial-burn events in locally over-diluted regions (Alkidas, 1999; Ji & Wang, 2009; Korakianitis et al., 2011). Few studies combine these emission responses with a same-point estimate of exhaust thermal availability, which is the specific focus of the present analysis.

3. MATERIALS AND METHODS

3.1. Engine Configuration and Test Facility

All experiments were conducted on a production-derived, four-cylinder, in-line, DOHC, naturally aspirated SI engine with multi-point sequential fuel injection (MPFI), mounted on a rigid steel test bench and coupled to an air-cooled AC (asynchronous) dynamometer (Schenck Dynas3 LI 250, 250 kW rated absorption). Coolant temperature was maintained at $80 \pm 2^\circ\text{C}$ by an external thermostatic circuit independent of the vehicle cooling system; lubricant sump temperature stabilised at $90 \pm 3^\circ\text{C}$. Full engine specifications and the ambient, intake, and lubricant conditions recorded during testing are presented in Table 1.

Table 1. Engine specifications and test conditions.

Parameter	Specification
Engine architecture	4-cylinder, in-line, DOHC, naturally aspirated
Displacement volume	1598 cm ³
Bore $\times$ Stroke	79.0 mm $\times$ 81.4 mm
Compression ratio	10.5 : 1
Number of valves	16 (4 per cylinder)
Rated maximum power	85 kW at 6000 rpm
Rated maximum torque	145 N·m at 4200 rpm
Fuel delivery system	Sequential multi-point fuel injection (MPFI)
Reference fuel	RON 92 Gasoline (LHV = 43.5 MJ/kg; density = 745 kg/m ³)
Ignition system	Coil-on-plug (COP) electronic ignition
Nominal idle speed	750 $\pm$ 50 rpm
Cooling system	External liquid-cooled test-cell thermostat circuit
Ambient air temperature	[... °C]

Parameter	Specification
Atmospheric pressure	[... kPa]
Relative humidity	[... %]
Intake air temperature	[... °C]
Intake manifold pressure (3000 rpm, full load)	[... kPa]
Lubricating oil	[brand, SAE grade, API class; fresh / ... h in service]
Lubricant sump temperature	90 ± 3°C

Figure 1 presents the schematic of the complete experimental test facility, showing the SI engine coupled to the Schenck Dynas3 LI 250 dynamometer, the standalone Motec M130 ECU with independent ITA and λ control, and the multi-instrument exhaust measurement suite.

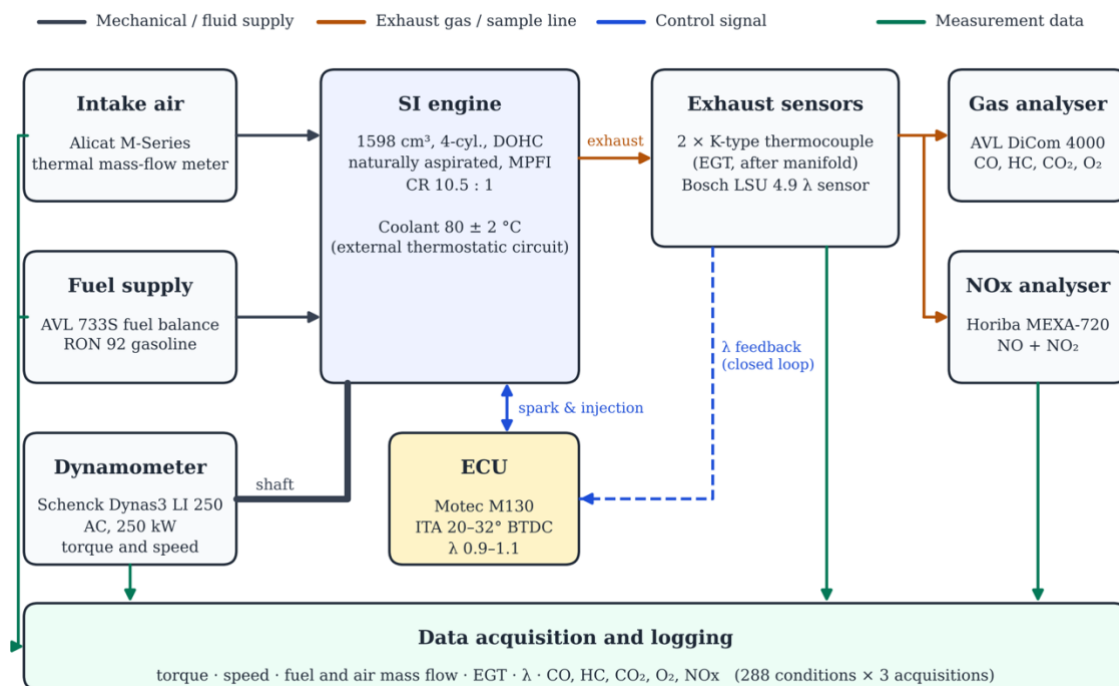


Figure 1. Schematic of the experimental facility.

Figure 1 schematic of the experimental facility, including the SI engine, AC dynamometer, programmable Motec M130 ECU, exhaust-gas measurement system, and data-acquisition unit. The full campaign comprised 288 operating conditions and three acquisitions per condition.

3.2. ECU Calibration Strategy and Experimental Design

The factory engine management system was replaced with a standalone programmable ECU (Motec M130) to enable independent control of spark timing and fuel-injection pulse width. Closed-loop lambda control used a Bosch LSU 4.9 wideband oxygen sensor installed downstream of the exhaust manifold collector. Four ITA values—20°, 24°, 28°, and 32° BTDC—were applied together with three target λ values: 0.9 (rich), 1.0 (stoichiometric), and 1.1 (lean). Each calibration was tested at six engine speeds and four load levels. The engine was stabilised for at least five minutes before three consecutive acquisitions were recorded at each operating condition.

Table 2. ECU calibration parameters and experimental test matrix.

Variable	Values / Range
Ignition Timing Advance (ITA)	20°, 24°, 28°, 32° BTDC
Excess air ratio (λ)	0.9 (rich), 1.0 (stoich.), 1.1 (lean)
Engine speed	1500, 2000, 2500, 3000, 3500, 4000 rpm

Variable	Values / Range
Engine load (% rated BMEP)	25%, 50%, 75%, 100%
Coolant temperature	$80 \pm 2^\circ\text{C}$
Stabilisation time per point	5 minutes minimum
Replicate runs per point	3 independent acquisitions
Total test campaign	288 operating conditions; 864 acquisitions

3.3. Measurement Instrumentation

Engine torque and speed were measured with the AC dynamometer. Fuel mass flow was measured gravimetrically with an AVL 733S fuel balance, while intake-air mass flow was measured using a calibrated Alicat M-Series thermal mass-flow meter. Exhaust mass flow was calculated as the sum of intake-air and fuel mass flow. CO, HC, CO₂, and O₂ were measured with an AVL DiCom 4000 gas analyser, while NO_x was measured with a Horiba MEXA-720 analyser. Two shielded K-type thermocouples installed downstream of the exhaust manifold were used to monitor exhaust-gas temperature. Lambda was monitored with the Bosch LSU 4.9 sensor. The principal instrumentation and stated uncertainties are summarised in Table 3.

Table 3. Principal measurement instrumentation and stated uncertainty.

Instrument	Measured parameter	Stated accuracy / uncertainty
Schenck Dynas3 LI 250	Brake torque and engine speed	$\pm 0.5 \text{ N}\cdot\text{m}$; $\pm 1 \text{ rpm}$
AVL 733S fuel balance	Fuel mass flow rate	$\pm 0.1\%$ of reading
Alicat M-Series thermal mass-flow meter	Intake-air mass flow rate	$\pm 0.8\%$ FS
AVL DiCom 4000	CO, HC, CO ₂ , and O ₂	CO $\pm 0.01\%$ vol; HC $\pm 1 \text{ ppm}$
Horiba MEXA-720	NO _x (NO + NO ₂)	$\pm 50 \text{ ppm}$
K-type thermocouples (2)	Exhaust-gas temperature	$\pm 1.5^\circ\text{C}$
Bosch LSU 4.9 wideband sensor	Excess-air ratio (λ)	$\pm 0.008 \lambda$

3.4. Data Reduction

Brake thermal efficiency (BTE) was calculated as:

$$\text{BTE } (\%) = P_{\beta} / (\dot{m}_f \times \text{QLHV}) \times 100 \quad \dots(1)$$

where P_{β} is brake power (kW), $\dot{m}_f$ is fuel mass flow rate (kg/s), and QLHV is the lower heating value of RON 92 gasoline (43.5 MJ/kg). Exhaust heat availability was estimated as sensible exhaust enthalpy above the ambient reference temperature:

$$Q_{\text{ex}} (\text{kW}) = \dot{m}_{\text{ex}} \times c_{p,\text{ex}} \times (T_{\text{ex}} - T_0) \quad \dots(2)$$

where $\dot{m}_{\text{ex}}$ is exhaust mass flow rate (kg/s), $c_{p,\text{ex}} = 1.08 \text{ kJ/kg}\cdot\text{K}$ is the assumed mean specific heat capacity of the exhaust gas (Domingues et al., 2013), T_{ex} is the measured exhaust-gas temperature ($^\circ\text{C}$), and $T_0 = 25^\circ\text{C}$. Q_{ex} is an estimate of thermal energy carried by the exhaust stream; it is not equivalent to net recoverable WHR power.

3.5. Basis for Integrated Comparison

Although the experimental matrix covered 288 operating conditions, all cross-metric comparisons in Sections 4.1–4.7 were restricted to 3000 rpm at full load. This restriction ensures that BTE, exhaust temperature, exhaust mass flow, Q_{ex} , and engine-out emissions are compared at the same speed-load point. Data from other speeds are used only to illustrate qualitative speed trends and are not combined in the calibration recommendation.

4. RESULTS AND DISCUSSION

4.1. Effect of Ignition Timing Advance on Brake Thermal Efficiency

Table 4 presents BTE across the ITA- λ matrix at 3000 rpm and full load. At $\lambda = 1.0$, BTE increased from 31.2% at 20° BTDC to a maximum of 34.2% at 28° BTDC, before decreasing to 33.1% at 32° BTDC. The response is consistent with improved combustion phasing as spark timing approaches MBT, followed by increasing negative compression work and heat-transfer losses when timing is advanced beyond MBT. The increase from 31.2% to 34.2% corresponds to a 9.6% relative BTE improvement and an approximately 8.8% reduction in brake-specific fuel consumption at constant fuel heating value.

Table 4. Brake thermal efficiency (%) at different ITA and λ conditions (3000 rpm, full load). Values are reported as mean $\pm$ expanded uncertainty ($k = 2$) from three acquisitions.

λ Condition	20° BTDC	24° BTDC	28° BTDC	32° BTDC
0.9 (Rich)	29.8 $\pm$ 0.4	31.5 $\pm$ 0.3	32.9 $\pm$ 0.3	31.7 $\pm$ 0.4
1.0 (Stoichiometric)	31.2 $\pm$ 0.3	32.8 $\pm$ 0.3	34.2 $\pm$ 0.2	33.1 $\pm$ 0.3
1.1 (Lean)	30.1 $\pm$ 0.5	31.8 $\pm$ 0.4	33.0 $\pm$ 0.4	32.2 $\pm$ 0.4

Figure 2 illustrates the same non-monotonic BTE response to spark timing and shows that the 28° BTDC calibration produced the highest BTE across the speed trend presented. Because MBT varies with operating condition, the 28° value should be interpreted as the optimum within the tested calibration grid rather than a universal timing value.

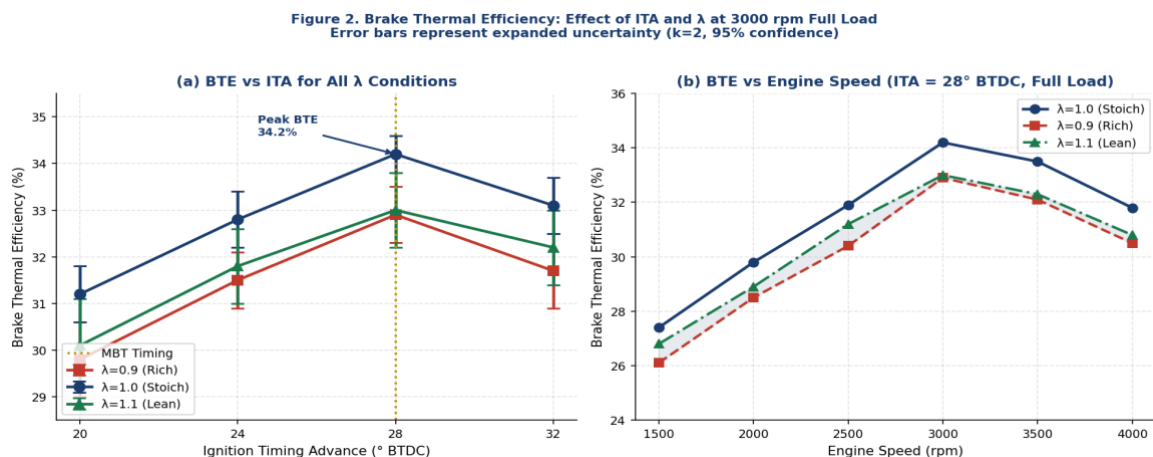


Figure 2. Brake thermal efficiency: (a) BTE versus ITA for all λ conditions at 3000 rpm and full load; the dashed line marks the highest measured BTE at 28° BTDC. (b) BTE versus engine speed at ITA = 28° BTDC and full load. Error bars represent the reported expanded uncertainty ($k = 2$).

4.2. Effect of Air-Fuel Ratio on Brake Thermal Efficiency

At the highest-BTE timing of 28° BTDC, stoichiometric operation produced BTE = 34.2%. Lean operation yielded 33.0%, a 1.2 percentage-point reduction, consistent with slower flame propagation and greater cycle-to-cycle variability as the mixture becomes diluted. Rich operation produced BTE = 32.9%, a 1.3 percentage-point reduction relative to stoichiometric operation because part of the supplied fuel could not be fully oxidised. The corresponding fuel-consumption penalty was approximately 3.9% for $\lambda = 0.9$ and 3.6% for $\lambda = 1.1$ relative to $\lambda = 1.0$ at the same brake output.

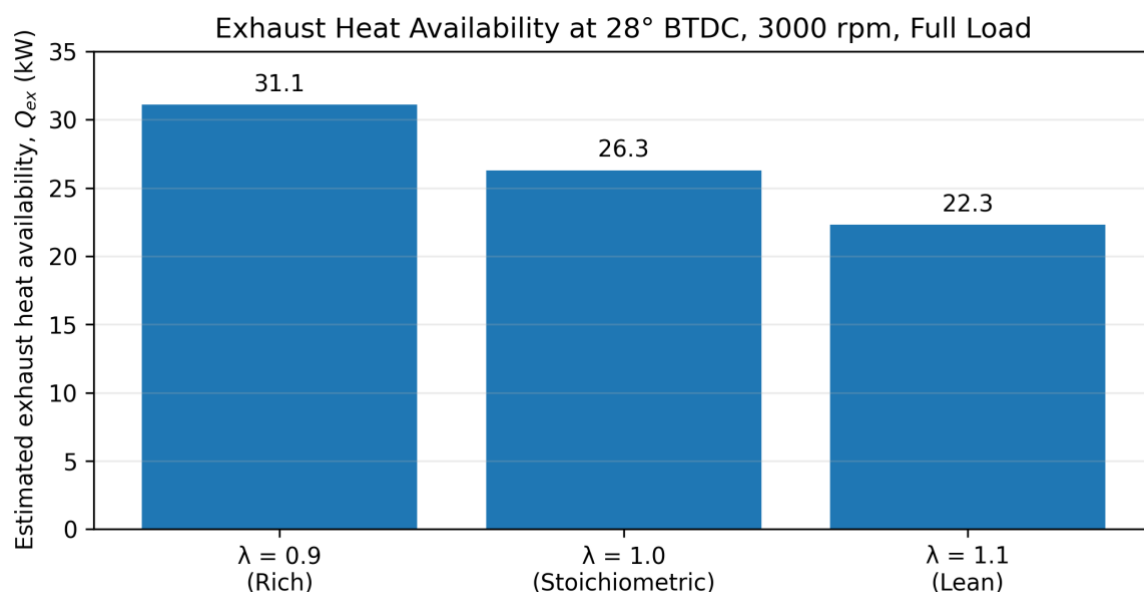
4.3. Exhaust Gas Temperature and Exhaust Heat Availability

Exhaust heat availability was recalculated at the common operating point of 28° BTDC, 3000 rpm, and full load using the measured exhaust mass flow and exhaust-gas temperature listed in Table 5. Q_{ex} was highest under rich operation (31.1 kW), followed by stoichiometric (26.3 kW) and lean operation (22.3 kW). Relative to $\lambda = 1.0$, rich calibration increased Q_{ex} by 18.5%, whereas lean calibration reduced it by 15.2%. The change was driven by the combined reduction in exhaust temperature and exhaust mass flow as λ increased.

Table 5. Thermal and performance metrics at 28° BTDC, 3000 rpm, and full load. Q_{ex} was calculated from Eq. (2) using the mean EGT and exhaust mass-flow values.

λ condition	EGT (°C)	Exhaust mass flow (g/s)	Q_{ex} (kW)	BTE (%)
0.9 (Rich)	698 ± 3	42.8 ± 0.9	31.1	32.9 ± 0.3
1.0 (Stoichiometric)	658 ± 2	38.4 ± 0.8	26.3	34.2 ± 0.2
1.1 (Lean)	621 ± 3	34.6 ± 0.7	22.3	33.0 ± 0.4

Figure 3 shows the same-point Q_{ex} comparison. Rich operation provides the largest exhaust thermal input, but the additional exhaust energy is obtained together with lower BTE and substantially higher CO and HC emissions. Consequently, maximum exhaust thermal availability should not be treated as the sole ECU-calibration objective.

**Figure 3.** Estimated exhaust heat availability at 28° BTDC, 3000 rpm, and full load. Values were calculated from the mean exhaust mass-flow rate and exhaust-gas temperature using Eq. (2).

4.4. Carbon Monoxide and Hydrocarbon Emission Characteristics

Table 6 summarises the engine-out emission response at 28° BTDC, 3000 rpm, and full load. CO decreased from 4.21% at $\lambda = 0.9$ to 0.91% at $\lambda = 1.1$, corresponding to a 78.4% reduction across the tested mixture range. HC displayed a V-shaped response with a minimum of 180 ppm at stoichiometry. Relative to $\lambda = 1.0$, HC increased by 58.3% under rich operation and by 22.2% under lean operation. The rich-side increase is consistent with oxygen deficiency, whereas the lean-side increase is consistent with slower oxidation and local quenching in over-diluted regions.

Table 6. Engine-out emission characteristics at different λ values (28° BTDC, 3000 rpm, full load). Values are reported as mean ± expanded uncertainty ($k = 2$); HC is expressed as hexane equivalent (ppm C6).

Emission Parameter	$\lambda = 0.9$ (Rich)	$\lambda = 1.0$ (Stoich.)	$\lambda = 1.1$ (Lean)
CO (% vol)	4.21 ± 0.08	1.82 ± 0.04	0.91 ± 0.03
HC (ppm vol, C6-equiv.)	285 ± 6	180 ± 4	220 ± 5
NOx (ppm)	980 ± 22	1450 ± 30	1190 ± 25
CO ₂ (% vol)	13.2 ± 0.2	14.8 ± 0.1	13.9 ± 0.2
O ₂ (% vol)	0.10 ± 0.01	0.42 ± 0.02	2.85 ± 0.06

Figure 4 shows the monotonic reduction in CO with increasing λ and the V-shaped HC response. The two sides of the HC curve arise from different mechanisms: oxygen limitation under rich operation and slower oxidation or local flame quenching under lean operation.

Figure 4. CO and HC Emission Characteristics: Effect of Air-Fuel Ratio (λ)
Error bars = expanded uncertainty at 95% confidence ($k=2$)

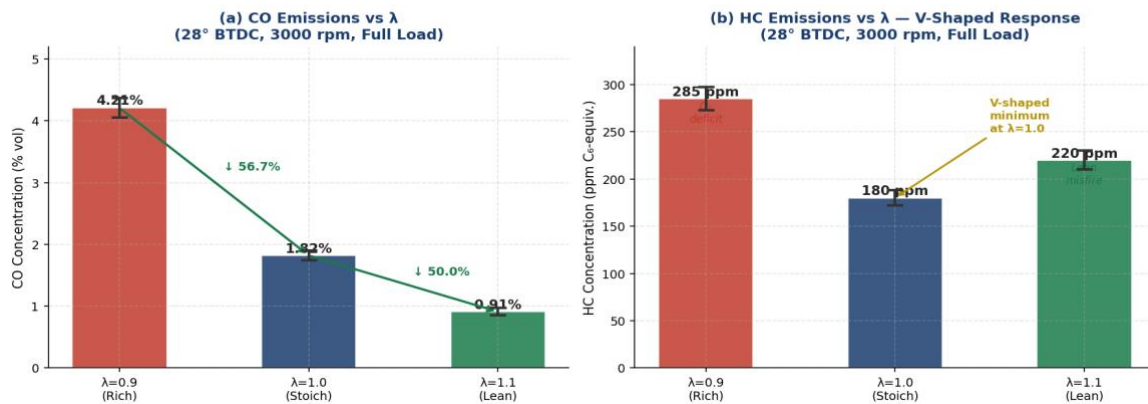


Figure 4. CO and HC engine-out emissions versus λ at 28° BTDC, 3000 rpm, and full load. (a) CO decreases by 78.4% from $\lambda = 0.9$ to $\lambda = 1.1$. (b) HC reaches its minimum at $\lambda = 1.0$ and increases under both rich and lean operation. Error bars represent the reported expanded uncertainty ($k = 2$).

4.5. NO_x Emission Characteristics

NO_x showed the strongest response to ignition timing among the reported emission species. At $\lambda = 1.0$, NO_x increased from 890 ppm at 20° BTDC to 1450 ppm at 28° BTDC and 1850 ppm at 32° BTDC, a total increase of 107.9%. The trend is consistent with the temperature sensitivity of the extended Zeldovich mechanism. At 28° BTDC, NO_x was lower under both rich and lean operation than at stoichiometry because rich operation limits oxygen availability and lean operation reduces combustion temperature. These are engine-out concentrations and do not represent tailpipe emissions after catalyst treatment.

Figure 5. NO_x Emission Characteristics: Effect of ITA and λ
Thermal NO_x formation governed by extended Zeldovich mechanism

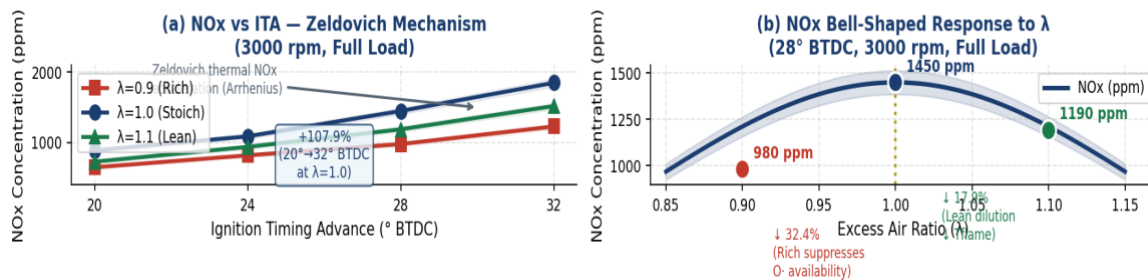


Figure 5. NO_x Emission Characteristics: (a) NO_x vs ITA showing 107.9% increase from 20° to 32° BTDC at $\lambda = 1.0$, driven by the Zeldovich thermal NO_x mechanism at elevated peak combustion temperatures. (b) Bell-shaped NO_x response to λ at 28° BTDC — peak at stoichiometry, reduced under both rich and lean conditions through different suppression mechanisms.

4.6. Full Calibration Matrix Analysis

Figure 6 compares CO, NO_x, and BTE across the complete 4×3 ITA– λ matrix at 3000 rpm and full load. The highest BTE occurs at 28° BTDC and $\lambda = 1.0$, whereas the minimum CO and minimum NO_x occur at different cells. The heatmaps therefore demonstrate that no single calibration independently minimises every emission species while also maximising efficiency. The highlighted cells identify the best observed value for each individual metric, not a global multi-objective optimum.

Figure 6. Full Calibration Matrix Heatmaps: CO, NOx, and BTE across 4 ITA Settings $\times$ 3 λ Conditions (3000 rpm, Full Load)
Gold border = optimal cell per metric

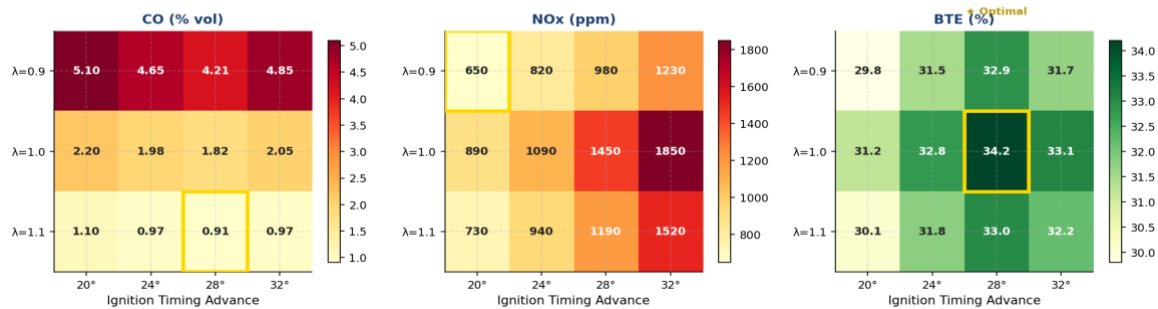


Figure 6. Full calibration-matrix heatmaps for CO (% vol), NOx (ppm), and BTE (%) across four ITA settings and three λ conditions at 3000 rpm and full load. The bordered cell indicates the best observed value for each individual metric.

4.7. Integrated Calibration Assessment at the Common Operating Point

At 3000 rpm and full load, the 28° BTDC and $\lambda = 1.0$ calibration provided the highest BTE (34.2%), the lowest HC (180 ppm), and an estimated Qex of 26.3 kW. Rich operation at the same timing increased Qex to 31.1 kW, but BTE decreased by 1.3 percentage points, CO increased by 131%, and HC increased by 58% relative to stoichiometric operation.

Lean operation at 28° BTDC reduced CO by 50% and NOx by 17.9% relative to stoichiometry, but BTE decreased by 1.2 percentage points, Qex decreased by 15.2%, and HC increased by 22.2%. On this basis, 28° BTDC and $\lambda = 1.0$ is the most balanced calibration among the tested conditions at the selected operating point. This conclusion is a same-point engineering comparison rather than a formal global Pareto optimum.

For practical vehicle application, final calibration would also need to account for transient operation, knock margin, catalyst temperature, fuel economy over a drive cycle, and regulated tailpipe emissions. The present engine-out steady-state results should therefore be used as a screening basis rather than as a direct certification recommendation.

4.8. Study Limitations

The findings are limited to one naturally aspirated engine, one gasoline grade, discrete spark and λ settings, and steady-state operation. Exhaust heat availability was estimated using a constant mean specific heat and represents sensible exhaust enthalpy above 25°C, not the net electrical or mechanical output of a WHR system. Emissions were measured upstream of after-treatment and are reported as concentrations rather than brake-specific or distance-specific values. Transient drive-cycle behaviour, catalyst conversion, knock intensity, and long-term repeatability were not evaluated.

5. CONCLUSION

A systematic ECU-calibration study was conducted on a 1598 cm³ naturally aspirated SI engine using four ITA values and three excess-air ratios across a broad speed-load matrix. To maintain a consistent basis, the integrated assessment was performed at 3000 rpm and full load. The highest BTE, 34.2%, occurred at 28° BTDC and $\lambda = 1.0$, representing a 9.6% relative improvement over 20° BTDC. At the same operating point, estimated exhaust heat availability was 31.1 kW for rich, 26.3 kW for stoichiometric, and 22.3 kW for lean operation. Rich calibration increased exhaust thermal potential but imposed substantial CO and HC penalties, while lean calibration reduced CO and NOx but decreased BTE and increased HC. Therefore, 28° BTDC and $\lambda = 1.0$ provided the best overall compromise among the tested same-point conditions. Future work should validate these findings under transient drive cycles, quantify catalyst conversion and knock margin, and measure actual WHR-system output rather than exhaust enthalpy alone.

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