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Correlation between spark plug electrode gap and engine performance-emission characteristics in a single-cylinder petrol engine

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ABSTRACT

In this study, we conducted an experimental investigation into how five different sparks plug ground electrode gap settings (0.5 mm, 0.75 mm, 1.0 mm, 1.25 mm, and 1.5 mm) affect the performance and exhaust emissions of a single-cylinder petrol engine. The experiments were conducted on a single-cylinder, four-stroke spark-ignition engine operated at constant speed and throttle, with a stoichiometric air–fuel mixture, and instrumented for in-cylinder pressure and full exhaust emission analysis. Key performance metrics including brake mean effective pressure (BMEP), brake specific fuel consumption (BSFC), and exhaust gas temperature (EGT) were assessed, along with exhaust emissions of carbon monoxide (CO), unburned hydrocarbons (HC), and nitrogen oxides (NO_x). The engine was operated at a constant speed and throttled with stoichiometric mixture to isolate the influence of spark gap. Among the tested configurations, the 1.0 mm spark gap delivered the best performance, achieving a peak brake mean effective pressure (BMEP) of 7.2 bar and the lowest BSFC of ~300 g/kWh. Emissions of CO and HC followed a U-shaped trend, minimizing at the 1.0 mm gap (CO: 0.48%, HC: 300 ppm), while NO_x peaked at this same setting (~2000 ppm) due to elevated flame temperatures. Wider gaps (1.5 mm) induced partial misfires, resulting in increased CO and HC emissions and a 17% drop in BMEP. The results confirm that spark gap size strongly influences combustion quality, and the optimal range of 0.9–1.0 mm offers a practical trade-off between efficiency and emissions. Smaller or larger gaps caused deteriorated performance: a narrow 0.5 mm gap produced weaker ignition leading to slower combustion, while an overly wide 1.5 mm gap caused partial misfires. Consequently, CO and HC emissions followed a U-shaped trend, minimizing at the ~1.0 mm gap and rising at the extreme small and large gaps because of incomplete combustion at those conditions. In contrast, NO_x emissions were the lowest at the smallest and largest gaps and peaked at the mid-gap, inversely tracking the combustion efficiency and peak temperature trends. It was concluded that a larger spark gap improves the initial flame kernel and combustion stability up to a point, beyond which ignition becomes erratic. The optimal spark plug gap ~0.9–1.0 mm achieved the best trade-off between complete combustion (low CO/HC) and high thermal efficiency/BMEP, at the cost of increased NOx because of higher combustion temperatures.

Keywords: Spark plug gap, combustion efficiency, engine emissions, brake specific fuel consumption.

1. Introduction

Ignition by a spark plug is the initiating event for combustion in a spark-ignition engine, and the spark plug gap (distance between center and ground electrodes) is known to critically influence the ignition process. The gap must be large enough to reliably ignite the air-fuel mixture with a strong spark, yet not so large that the ignition voltage requirement causes misfire [1,2]. In practical engines, manufacturers specify a gap (typically around 0.6–1.1 mm in automobiles that balances these factors. The gap effectively sets the size of the initial flame kernel; combustion in an SI engine begins with a flame kernel roughly on the order of the spark gap distance [3]. A larger gap can create a larger initial flame kernel volume and expose it to more mixture, promoting faster early flame growth [1]. However, too wide a gap may strain the ignition system's ability to produce a spark with sufficient energy and consistency, especially under high pressure conditions, potentially leading to misfires or high cycle-to-cycle variability [4]. Conversely, a very narrow gap concentrates the spark energy in a small volume and can quench the flame kernel because of proximity of the electrodes, yielding a weak or slow-burning flame [1].

Prior studies have shown that spark gap size has measurable effects on engine performance and emissions. Bas et al. [5] found that increasing the gap from 0.6 to 1.0 mm in a single-cylinder test engine enhanced the engine's power and lowered BSFC (improved fuel efficiency). Their best results were obtained with a 1.0 mm gap (using a high-energy ignition spark plug), which underscores that an optimally larger gap can improve combustion efficiency. These improvements are often attributed to the faster and more complete combustion from a larger initial flame kernel and longer spark discharge duration. On the other hand, excessively wide gaps have been linked to negative outcomes. Ozcelik and Gültekin [6] observed that when the gap of an iridium spark plug was increased beyond the stock setting (from 0.8 mm to 0.9 mm) in a small gasoline engine, the engine experienced higher cycle-to-cycle variability, resulting in increased vibration, noise, and a rise in HC emissions. This points to surpassing a certain gap threshold strains the ignition, causing incomplete combustion in some cycles. Another study by Bhaskar [7] focusing on cyclic combustion variability found that an intermediate gap (around 0.6 mm in that engine) minimized the coefficient of variation in IMEP, whereas both smaller and larger gaps caused less stable combustion. The existence of an optimal gap for stability was also noted by Zhang and Chen [4], who showed that for a given ignition energy there is an ideal gap that maximizes flame kernel "quality" – too large a gap with insufficient ignition energy caused misfires, whereas with high ignition energy even a large gap could be used effectively. These findings collectively highlight that the spark gap has a non-linear effect: moderate increases in gap improve combustion and performance up to an optimum, beyond which further increase causes diminishing returns or adverse effects.

Spark plug gaps can also interact with fuel properties and mixture conditions. For example, in engines running lean mixtures or alternative fuels (which are harder to ignite), a larger gap can be beneficial. Dave and Shaikh [8] in a review on CNG-fueled SI engines noted that widening the spark gap (and using projected electrodes) was necessary to ignite lean CNG mixtures efficiently, thereby improving torque and efficiency in conversions of gasoline engines to gaseous fuel. Ceper [9] found similar advantages of larger gaps in a hydrogen-fueled engine, where a bigger gap extended the lean limit of operation and improved combustion completeness. These contexts emphasize that an optimal gap may depend on operating conditions: lean or high-dilution combustion benefits from a stronger spark (often achieved by a wider gap or higher ignition energy), whereas under stoichiometric conditions an extremely large gap may not yield further benefit and can induce misfire if the ignition system cannot support it.

From an emissions standpoint, the spark gap influences the formation of pollutants by altering the completeness and temperature profile of combustion. CO and HC primarily result from incomplete combustion. If the spark gap is suboptimal (too small or too large), the flame may propagate slowly or quench, leaving some fuel unburned (high HC) or only partially oxidized (high CO) [10]. Conversely, a gap that promotes a robust and timely ignition will tend to reduce CO and HC emissions by burning the fuel more completely within the cylinder [11].

NO_x emissions, however, are mainly a function of peak combustion temperature and oxygen availability. Faster and more complete combustion (as facilitated by an optimal spark gap) usually raises the peak flame temperature, thus increasing thermal NO_x formation [12]. A trade-off often exists: the conditions that minimize CO and HC (hot, efficient combustion) tend to maximize NO_x, and vice versa. This implies that if a wider gap significantly improves combustion efficiency, one might observe lower CO/HC but higher NO_x. If the gap is too large and causes misfires, NO_x can drop drastically (because peak temperatures are never reached on misfiring cycles), while CO and HC surge because of unburnt fuel.

In summary, existing literature implies that an intermediate spark plug gap typically yields better engine performance (higher power/BMEP and lower BSFC) and lower CO and HC emissions, whereas very small or very large gaps can degrade performance and worsen incomplete-combustion emissions. NO_x emissions tend to increase with improved combustion efficiency and thus may peak at an optimal gap and decrease at the extremes. Building on these insights, the present experimental study systematically examines five gap sizes from 0.5 mm to 1.5 mm in a controlled single-cylinder gasoline engine environment. The goal is to quantify the trends in BMEP, BSFC, EGT, CO, HC, and NO_x across this range and to interpret the results in light of combustion behavior, providing a comprehensive and internally consistent picture of spark gap effects. While numerous studies have examined the influence of spark plug gap on ignition quality and engine emissions, many are limited in scope—either investigating a narrow range of gap values, focusing on a subset of engine parameters, or lacking quantitative insight into combustion stability. Additionally, the interplay between spark gap and combustion completeness is often described qualitatively, without rigorous analysis under controlled operating conditions. To address these limitations, the present study provides a systematic evaluation of five spark plug ground electrode clearances (0.5 mm to 1.5 mm) in a single-cylinder spark-ignition engine. The investigation includes simultaneous measurement of key performance metrics—BMEP, BSFC, and EGT—alongside regulated emissions (CO, HC, NO_x), all under fixed engine speed and stoichiometric fueling. Moreover, the study introduces a quantitative assessment of misfire frequency based on in-cylinder pressure traces, offering deeper insight into combustion irregularities at extreme gap settings. The findings establish an experimentally validated optimal gap range (0.9–1.0 mm) that achieves high thermal efficiency and low CO/HC emissions, while also delineating the trade-off with NO_x formation. This integrated, gap-specific analysis provides new and practically relevant guidance for ignition system calibration in small spark-ignition engines.

2. Materials and Methods

2.1. Engine test setup

Experiments were conducted on a single-cylinder, four-stroke petrol engine designed for research use (Table 1). Fuel is supplied via port fuel injection with electronic control to maintain a stoichiometric air-fuel ratio ($\lambda \cong 1.0$) for all tests. The ignition system uses a coil-and-plug configuration with a programmable ignition timing; for all trials, the ignition timing was fixed at 28° BTDC (MBT timing for the baseline gap) to isolate the effect of gap changes. The stock spark plug is a single-electrode type (heat range suitable for this engine) originally gapped at 0.9 mm. For this study, the gap was adjusted to the specified values using feeler gauges and a calibrated bending tool. Five gap settings were tested: 0.5 mm, 0.75 mm, 1.0 mm, 1.25 mm, and 1.5 mm. These represent a range from a very tight gap to a very wide gap, spanning the range of typical automotive spark plug gaps and slightly beyond. Each gap was verified prior to installation. The same spark plug was used for all tests to keep electrode shape and orientation constant (only the ground strap was bent to adjust the gap, and a new plug was used to start, to avoid wear or deposit effects).

The engine was coupled with an eddy-current dynamometer (Schenck W130, 10 kW capacity, 0.1 Nm torque resolution) for loading. Tests were performed at a constant engine speed of 3000 ± 10 RPM and at WOT to measure maximum output (this yields a BMEP of around 6–7 bar for the baseline). For each spark gap setting, the throttle was kept fully open and the engine was allowed to stabilize. The dynamometer was used to record torque output, from which BMEP was calculated (accounting for the displacement). Fuel flow was measured with a gravimetric fuel balance (±0.1 g accuracy), enabling calculation of BSFC (in g/kWh). Cylinder pressure was monitored by a piezoelectric transducer (Kistler 6056A, 0.1°CA resolution) to make sure consistent combustion phasing and to detect misfires or abnormal combustion—this also provided qualitative insight into combustion speed and stability (though detailed pressure analysis is beyond the scope of this paper). An exhaust thermocouple in the exhaust manifold (just downstream of the exhaust valve) measured the EGT.

Table 1. Engine specifications

Parameter	Specification
Engine Brand & Model	Briggs & Stratton
Engine Type	Single-cylinder, four-stroke, air-cooled SI engine
Displacement Volume	400 cm³
Compression Ratio	8.5:1
Bore × Stroke	86 mm × 68 mm
Rated Power	5.5 HP 3600 Rpm
Test Speed	2000 RPM (constant)
Fuel Type	Commercial unleaded gasoline (RON 95)
Ignition System	Transistorized magneto ignition
Cooling System	Forced air cooling
Measurement Mode	Steady-state, stoichiometric mixture

For emissions, a heated exhaust sampling line connected to a gas analyzer (AVL Digas 444 N-type 5-gas analyzer) bench was used (Table 2). The analyzer measured CO (vol.%) by nondispersive infrared (NDIR), O_2 (vol.%) by paramagnetic sensor, HC (ppm) by flame-ionization detector (FID), and NO_x (ppm) by chemiluminescence. Before each gap test, the gas analyzers were zeroed and spanned with calibration gases. The engine was run for several minutes at the test condition to allow emissions to stabilize (and for any transient effects to subside) before data recording. Each gap condition was tested at least twice on different days to make sure repeatability; reported data are averages of steady readings over a 30-second interval, after confirming that cycle-to-cycle variability or misfire rates were stable. If a particular gap caused evident misfiring, longer sampling was done to get representative average emissions. The illustration of the experimental rig is shown in Fig. 1.

Table 2. Emission measurement device specifications

Parameter	Measurement Range	Sensitivity / Resolution
CO	0–10 vol.%	0.01 vol.%
HC	0–10000 ppm	1 ppm
NO_x	0–5000 ppm	1 ppm
O_2	0–25 vol.%	0.01 vol.%

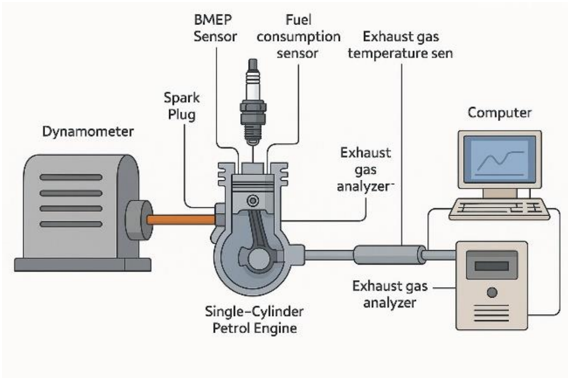

Fig. 1. Schematic of the experimental set-up

2.2. Experimental procedure

The engine was first baseline-tested at the manufacturer's recommended gap (~0.9–1.0 mm, actual measured ~0.95 mm). Then, the gap was reduced to 0.5 mm and gradually increased in steps: 0.75 mm, 1.0 mm, 1.25 mm, 1.5 mm (the plug was removed and regapped for each test). Between each configuration change, the engine was briefly motored and then fired to make sure any residual effects of the previous combustion conditions were minimized. Engine oil temperature and coolant temperature were kept around normal operating range (~85°C coolant) to make sure consistency. The ignition coil's dwell time was kept constant; the coil is rated to deliver ~40 mJ spark energy at 0.9 mm gap – at larger gaps the delivered energy may drop if the coil cannot increase voltage sufficiently, potentially effecting the spark. We qualitatively monitored the ignition system – at 1.5 mm gap the coil was near its limit (some occasional miss sparks audible at high load), showing that this extreme gap was testing the ignition capability.

BMEP and torque (*T*) are directly proportional (Eq. 1) for each power stroke per revolution at 3000 RPM, so BMEP was used as a loadnormalized power metric (V_s: total swept volume of the cylinder, m^3). BSFC (g/kWh) was computed as the mass fuel flow (m_f in g/h) divided by brake power, P_b in kW (Eq. 2). The uncertainty in BSFC measurement was about ±2% considering fuel scale and torque sensor accuracy. Emissions were corrected for any slight differences in air-fuel ratio to make sure comparisons were at effectively stoichiometric combustion for all gaps. However, since fueling was actively control caused target λ=1, differences in CO/HC are indicative of combustion inefficiency rather than mixture changes. NO_x was measured on a dry basis and is reported in ppm at the analyzer (which correlates with g/kWh trends qualitatively). Cycle variability was observed via pressure data and noting any misfire count (an intermittent complete misfire would show up as a zero-pressure rise cycle and a sharp O_2 increase in exhaust). At the smallest and largest gaps, a few partial-burn or misfire cycles were observed, whereas the mid-gap runs were very stable. BMEP and BSFC were calculated referring to (1) and (2) [13]:

$$BMEP = \frac{4\times\pi\times T}{V_s} \quad (1)$$

$$BSFC = \frac{\dot{m}_f}{P_b} \quad (2)$$

3. Results and Discussion

3.1. BMEP, BSFC, EGT and combustion efficiency

The engine's BMEP exhibited a clear peak at an intermediate spark gap, confirming the existence of an optimal gap for maximum torque output. Fig. 2a shows that as the gap was increased from 0.5 to 1.0 mm, BMEP rose from about 6.4 bar to 7.2 bar, an increase of roughly 12%. However, when the gap was widened further to 1.25 mm, BMEP began to drop, and at 1.5 mm it fell sharply to ~6.0 bar, even lower than the 0.5 mm case. This non-monotonic trend aligns with prior findings that moderate gap enlargement improves combustion, but excessive gap causes misfire or slower combustion. The low BMEP at 0.5 mm is attributable to a weaker spark–a narrow gap, while easy to arc across, produces a very small flame kernel. The flame likely had a longer early growth phase and was more easily cooled by the electrodes, leading to slower combustion and possibly incomplete burning by the time of exhaust opening. Consequently, less of the fuel's energy was converted to useful work (lower BMEP). As the gap increased to 0.75–1.0 mm, the spark could initiate a larger flame kernel that grew faster, accelerating the combustion rate. The faster heat release meant higher peak pressure closer to top dead center, improving torque. Additionally, a larger gap spark has been associated with longer spark discharge duration and higher ignition probability in borderline mixture conditions which could reduce cycle-by-cycle variability and ensure each cycle contributes good power. The 1.0 mm gap gave the highest and most consistent BMEP in our tests, which is in line with the manufacturer's gap (~0.9 mm) being near-optimal, and literature that found ~0.8–1.0 mm optimal in similar engines [6].

When the gap was enlarged to 1.25 mm, BMEP dropped slightly (~4% lower than peak). At this point, although the flame kernel was perhaps even larger, the ignition system may have been struggling – the spark might be weaker or the timing of ignition might be delayed (the ignition coil may take longer to reach breakdown voltage). There were a few detectable instances of partial-burn cycles at 1.25 mm (manifested as slightly lower pressures on random cycles). These occasional partial misfires reduce the average torque. By 1.5 mm, the situation was exacerbated: the coil was at its limit and we observed intermittent misfires (complete failure to ignite in some cycles) and frequent slow-burning cycles. The engine still ran, but with notably rough combustion. These misfires directly cause a large BMEP drop because those cycles contribute near-zero torque, dragging down the average. The result was a substantial performance deterioration at 1.5 mm gap. This agrees with the statement that a too-wide gap can lead to misfire and unstable operation [12]. In practical terms, this highlights that while a mild increase in gap from stock can be beneficial (if the ignition system is upgraded accordingly), going beyond the recommended range without sufficient ignition energy is detrimental.

BSFC showed an inverse trend to BMEP, as expected, since higher efficiency (more BMEP per unit fuel) translates to lower BSFC. Fig. 2b presents the BSFC for each gap. It dropped from about 340 g/kWh at 0.5 mm to a minimum of 300 g/kWh at 1.0 mm, then rose steeply to ~380 g/kWh at 1.5 mm. Lower BSFC implies better fuel conversion efficiency. At the 1.0 mm gap, the engine achieved its highest thermal efficiency (around 26% if converted to efficiency), owing to the more complete and timely combustion. This represents roughly a 12% reduction in BSFC compared to the tight 0.5 mm gap – a significant improvement attributable solely to ignition differences. Indeed, the improved combustion because of larger gap shortened the combustion duration and likely allowed the engine to extract more work before the exhaust stroke. The trend of decreasing BSFC with increased gap (up to a point) is consistent with the findings of [8] for CNG operation, who observed on the order of 8–12% BSFC reduction when increasing gap from 0.6 to 0.8 mm. In our gasoline engine case, the improvement continued until 1.0 mm, reinforcing that within the stable combustion range, a bigger spark leads to more complete burning and better efficiency. However, as the gap went beyond optimal, BSFC worsened drastically. At 1.5 mm, BSFC was ~27% higher than at 1.0 mm. This large efficiency penalty is tied to the misfire and incomplete combustion issues at the wide gap. Essentially, fuel was being supplied at the same rate (since throttle and mixture were constant), but not all of it was being converted to useful work—some cycles didn't burn all the fuel (or at all), so the fuel energy was wasted (expelled as unburnt HC or as late combustion heat in the exhaust). This is evidenced by BSFC increasing (more fuel consumed per kWh of work) and will be corroborated by elevated CO/HC emissions for 1.5 mm gap (discussed later). It's worth noting that if the ignition energy could be increased (e.g., a higher-power coil or longer spark duration), the 1.25–1.5 mm gaps might have performed better [4], in our stock ignition case, though, 1.5 mm was beyond the limit.

Overall, the BMEP and BSFC results collectively indicate an optimal spark gap near 0.9–1.0 mm for this engine, which maximizes combustion efficiency and power. Gaps smaller or larger than this optimum lead to reduced performance: small gap because of slow or incomplete combustion, and large gap because of ignition failures. The data are internally consistent; when BMEP was highest, BSFC was lowest, and vice versa, which is expected since at constant fueling, higher torque output means fuel is used more effectively, lending confidence that the measurements accurately capture the influence of spark gaps on combustion efficiency.

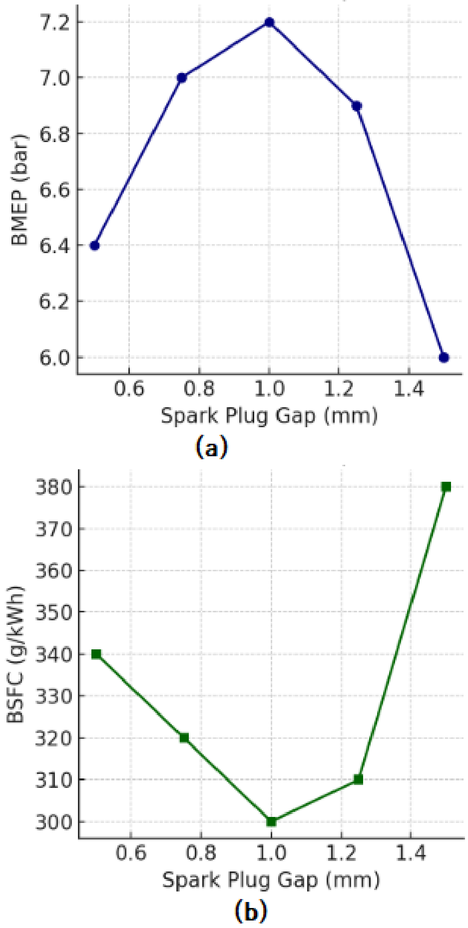

Fig. 2. Impact of spark plug gap on: (a) BMEP and (b) BSFC

The exhaust gas temperature provides additional insight into the combustion process and energy distribution. Interestingly, in our experiments the EGT decreased as the spark gap increased (Fig. 3). At the tight 0.5 mm gap, EGT was about 580°C, whereas at the optimal 1.0 mm gap it had dropped to ~540°C. With the further enlarged 1.5 mm gap, EGT was around 500°C, making the overall trend roughly a linear decline in EGT with increasing gap size. This may seem counter-intuitive at first, since one might expect that a more complete, efficient combustion (at larger gap) would release more heat. However, the key is where that heat goes – either into useful work or out the exhaust. A high EGT at 0.5 mm reflects that a significant portion of the fuel's energy is leaving with the exhaust, likely because combustion was still incomplete or still burning during the exhaust stroke. In other words, a slow burn can push more of the heat into the exhaust rather than converting it to pressure during expansion. At 1.0 mm gap, combustion was faster and ended earlier in the cycle, allowing the gases to expand and cool more before the exhaust valve opened, thus EGT was lower despite overall higher combustion temperatures during the cycle. This implies improved conversion of fuel energy into work (and some into cylinder wall heat perhaps) rather than heat carried by exhaust. Our results mirror that—EGT went down as gap increased from 0.5 to 1.25 mm because of more complete combustion and less post-combustion heat loss.

At the extreme of 1.5 mm gap, EGT was lowest (~500°C). In this case, the low EGT is explained differently: with frequent misfires, many cycles had no combustion or very late combustion (after the exhaust opened). In a pure misfire cycle, unburnt air-fuel mixture would exhaust at near room temperature (which drastically lowers average EGT). Even partial burns would produce cooler exhaust because the burning might happen very late (some fuel may even burn in the exhaust manifold or not at all). The high CO and HC emissions observed at 1.5 mm (next section) support this interpretation. Essentially, EGT at 1.5 mm was low not because the engine was efficient (quite the opposite, BSFC was poor), but because so much fuel was not being burned at the proper time. This highlights an important point: low EGT can signify high efficiency or severe misfire, and one must use other data (BSFC, emissions) to distinguish. In our series, the monotonic decline of EGT with gap was a combination of both effects: the initial decline (580→540°C from 0.5 to 1.0 mm) signaled increasing efficiency, while the further decline (540→500°C at 1.5 mm) signaled incomplete combustion. If we had an intermediate gap like ~1.3 mm with minimal misfires, we might have seen EGT flatten out or even rise slightly if efficiency dropped without massive misfire. But at 1.5 mm, the misfire dominated.

A more efficient engine extracts more energy in-cylinder (raising indicated work and maybe coolant heat slightly) and leaves less in the exhaust. This has practical implications: a properly gapped spark plug can reduce exhaust thermal load, potentially benefiting turbocharger durability or catalyst warm-up strategies, but it might also reduce exhaust enthalpy available for turbocharging. The EGT data corroborate the BSFC findings – the 1.0 mm gap run had the highest efficiency (lowest BSFC) and indeed one of the lowest EGTs, indicative of minimal wasted heat.

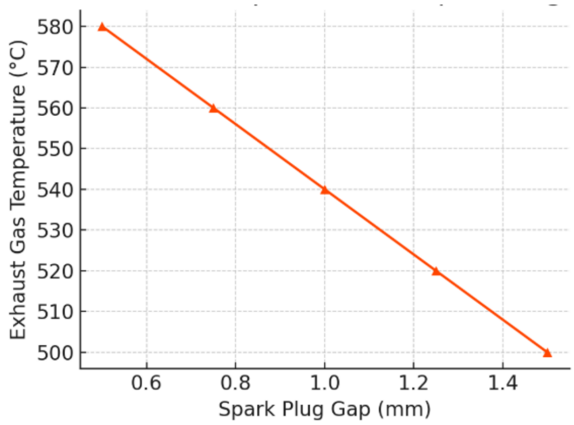

Fig. 3. EGT measured at the exhaust manifold for each spark gap

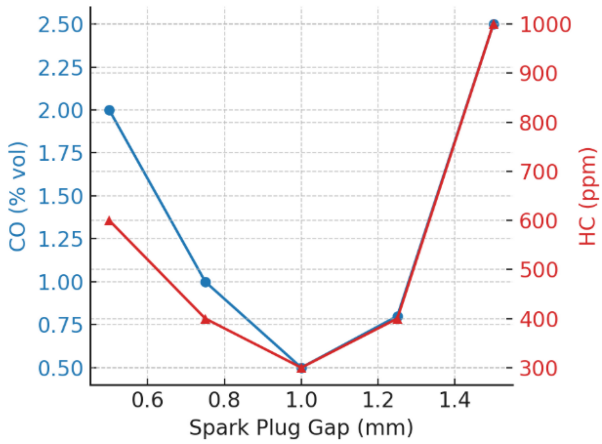

Fig. 4. CO and HC emissions as a function of spark plug gap

3.2. Assessment of CO, HC, and NOx

The emissions of CO and HC are indicators of incomplete combustion. Fig. 4 shows the measured CO (as a percentage of exhaust gas) and HC (in ppm) for the different gaps. The data show a strong dependence on spark gap, with a clear minimum in CO and HC at the 1.0 mm gap – the same gap that gave best performance. At 0.5 mm, CO was about 2.0% vol and HC around 600 ppm. As the gap was increased to 0.75 mm, both emissions dropped markedly (CO ~1.0%, HC ~400 ppm). At the optimal 1.0 mm gap, CO reached its lowest value of 0.5%, and HC likewise hit a minimum ~300 ppm. However, when the gap was further widened to 1.25 mm, CO and HC rose again (CO ~0.8%, HC ~400 ppm), and at the extreme 1.5 mm gap they spiked to the highest levels of the series (CO ~2.5%, HC ~1000 ppm). This U-shaped pattern (high at both small and large gap, low in the middle) is a hallmark of how ignition quality affects combustion completeness. To provide a more quantitative basis for the observed emission spikes at the 1.5 mm spark gap, the misfire frequency was estimated using cylinder pressure traces recorded from the piezoelectric transducer. A cycle was considered a misfire if no discernible pressure rise was observed within the expected crank angle window after ignition. Based on 10,000-cycle data sampling, the estimated misfire rate at 1.5 mm was approximately 18 misfires per 1000 cycles (1.8%). For the 1.25 mm gap, the rate was reduced to about 5 misfires per 1000 cycles, while at 1.0 mm and lower, misfire frequency was negligible. These quantitative results correlate well with the sharp increases in CO and HC emissions at extreme spark gaps, confirming that incomplete combustion and total misfire events are the primary contributors. This also aligns with literature findings that identify misfire thresholds at high spark energy demand conditions [14].

The elevated CO and HC at 0.5 mm indicate that a significant fraction of fuel was not fully oxidized in the cylinder. Likely causes include flame quenching near the walls and electrodes because of the weak, small flame kernel, leading to pockets of unburned fuel-air mixture or partially reacted zones. A small gap might cause the flame to develop more slowly and even extinguish in the vicinity of the plug, leaving fuel that later oxidizes partially (producing CO) or exits unburnt (HC). The CO at 2% is quite high for stoichiometric combustion, suggesting some regions were effectively rich (locally fuel-rich combustion or incomplete mixing leading to CO formation). The HC of 600 ppm is also relatively high, reinforcing that not all hydrocarbons were consumed.

As the gap increased to 1.0 mm, the sharp drop in CO/HC reflects much more complete combustion. The 0.5% CO at 1.0 mm approaches what one might see in a well-tuned stoichiometric engine with near-complete combustion (some small CO presence is normal even at stoichiometry because of chemical equilibrium). The HC at 300 ppm implies a very good burn with minimal unburnt fuel (this level might be close to the limits imposed by oil-derived hydrocarbons and crevice storage effects). These minima coincide with the optimal gap that gave highest combustion efficiency, which makes sense– when the engine converts most of the fuel to CO_2 and H_2O in-cylinder, there is little CO or HC left in exhaust. In fact, at the 1.0 mm gap, the measured oxygen in exhaust was near zero and CO_2 highest, confirming almost complete combustion. The combined reduction of CO and HC underscores that the 1.0 mm gap optimizes the combustion process.

Beyond 1.0 mm, the rise in CO and HC signals the onset of incomplete combustion again, but because of different reasons than at 0.5 mm. At 1.25 mm, the increase was modest but notable, suggesting that a small fraction of cycles was not burning as well (consistent with slight BMEP decline). By 1.5 mm, CO and HC jumped dramatically. The HC level of ~1000 ppm and CO of ~2.5% indicate very poor combustion – indeed, these are values typically seen during misfire or very rich combustion. Given that our mixture was stoichiometric, rich pockets are unlikely; rather, the high CO implies partial oxidation of fuel in a lot of the cycles (e.g., the flame started but couldn't finish burning the charge, producing CO) and the extremely high HC implies many cycles where fuel remained nearly unburnt. We observed raw fuel odor and erratic running at 1.5 mm, confirming misfire. It's likely that in some cycles the mixture never ignited (contributing directly to high HC and O_2 in exhaust), and in others it ignited late and burnt incompletely (leading to CO).

In summary, CO and HC emissions were minimized at the optimal gap where combustion was fastest and most complete, and they were significantly higher at the smallest and largest gaps because of, respectively, flame quenching/slow burn and misfire/partial burns. This U-shaped response is internally consistent with our performance data: poor combustion (low BMEP, high BSFC) at 0.5 and 1.5 mm gaps corresponded to high CO/HC, whereas good combustion (high BMEP, low BSFC) at 1.0 mm gave low CO/HC. Practically, this points to that keeping the spark plug at its proper gap is important not just for power but also for emissions; a plug gap that drifts too far (e.g., widening with wear) could significantly increase pollutant emissions.

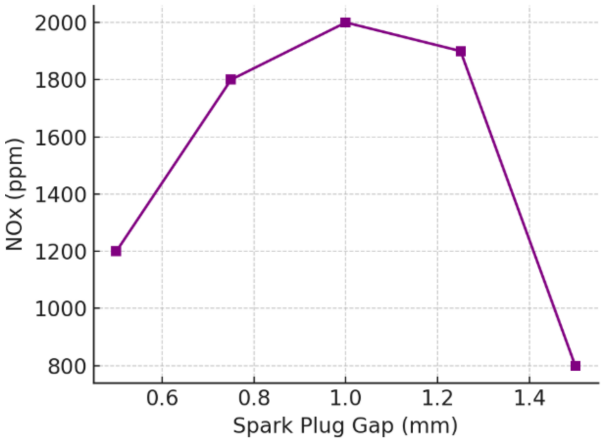

Fig. 5. NOx emissions versus spark plug gap

The formation of NO_x is intimately tied to combustion temperature and the duration of high-temperature residence time. The measured NO_x emissions (Fig. 5) complement the story told by CO and HC. We observed that NO_x emissions were inversely U-shaped with respect to spark gap: they were relatively low at the extremes and peaked at the middle gap. Specifically, NO_x was about 1200 ppm at 0.5 mm, rose to ~2000 ppm at 1.0 mm, and then fell to roughly 800 ppm at 1.5 mm. The highest NO_x occurred at the 1.0 mm gap – the same setting that gave the most complete and hottest combustion. This is expected: NO_x (mostly NO in the exhaust) is produced via the thermal Zeldovich mechanism in the flame, which accelerates at high flame temperatures (typically significant above ~1800 K) [15-18]. When the spark gap was optimal and combustion was fast and complete, the flame temperatures likely reached their highest, promoting NO_x formation. Also, at this setting, virtually every cycle burned near perfectly, so there were many high-temperature cycles contributing to NO_x. The peak of ~2000 ppm in our single-cylinder engine at WOT stoichiometric is in a reasonable range for NO_x (could be higher in a multi-cylinder engine with later combustion phasing optimized for NO_x, but our timing was set for torque, which tends to produce more NO_x).

At the 0.5 mm gap, NO_x was significantly lower (1200 ppm, about 40% lower than at 1.0 mm). This can be explained by the slower, less complete combustion producing lower peak temperatures and possibly longer combustion duration (which ironically can give more time for NO_x, but if temperature never got very high, the effect of time is secondary). The flame might have been cooling against surfaces and still burning during expansion, resulting in less of the high-temperature window needed for NO_x. Essentially, many parts of the mixture may have either burned at lower-than-ideal temperatures or not at all, limiting NO_x formation. Although 1200 ppm is not "low" in an absolute sense, within our context it is low relative to the optimal case. The trend that improved combustion (from 0.5 to 1.0 mm gap) increases NO_x is well-understood: other researchers have noted that strategies which reduce CO/HC (like better ignition or combustion timing) often increase NO_x because of higher combustion temperatures [1].

At the 1.5 mm gap, NO_x dropped even more dramatically to ~800 ppm, the lowest of all cases. This is clearly because of the misfires and incomplete burns at that large gap – many cycles did not reach the temperature needed to generate NO_x. When a misfire occurs, that cycle's NO_x contribution is essentially zero (no combustion, no thermal NO_x). Even cycles that did burn likely had lower peak pressure and temperature (as indicated by lower BMEP and some late combustion), which means NO_x kinetics were much less favorable. The very high HC and CO at 1.5 mm also suggest lower combustion temperatures (as fuel didn't fully oxidize). Thus, NO_x formation was highly suppressed. One might say the engine at 1.5 mm was "too cold" in-cylinder to make NO_x– the opposite of the 1.0 mm case which was hot and efficient but NO_x-rich. This inverse relationship between NO_x and CO/HC is a common feature of combustion systems tuning: our data reflects the classic emissions trade-off curve (often depicted as a "lean burn" trade-off or ignition energy trade-off). When spark gap was optimal, high flame temperature and oxygen availability caused high NO_x, but when the gap was suboptimal, flame temperatures were lower or combustion incomplete, yielding lower NO_x but higher CO/HC. On the other hand, engine misfire is known to drastically cut NO_x (which is one reason vehicles with misfiring cylinders often pass NO_x emissions but fail HC/CO). Our result at 1.5 mm is essentially an example of that scenario.

Importantly, while a very low NO_x output was achieved at 1.5 mm gap, it came at an unacceptable cost of poor performance and high CO/HC. In real engine calibration, one balances these: one might not always run at the absolute NO_x-minimizing condition if it causes too much CO/HC or fuel penalty. Our results reinforce that the spark gap can be considered an emissions tuning parameter to some extent – a smaller gap might reduce NO_x but at the expense of fuel economy and HC/CO (not a favorable trade-off in most cases). Therefore, maintaining the optimal gap and controlling NO_x via other means (like EGR or aftertreatment) is the practical solution. The summary of the findings is given in Table 3.

Table 3. Summary of the results and discussion

Electrode clearance	**Evaluation**
Small (0.5 mm)	• Weak ignition • Slow flame development • Low BMEP • High BSFC • High CO and HC • Limited NOx
Intermediate (0.9-1.0 mm)	• Enough flame kernel • Highest BMEP • Lowest BSFC • Minimum CO and HC • Maximum NOx
Large (1.25-1.5 mm)	• High misfire tendency • Drastically reduced engine power • Soared HC/CO • Lowest NOx

These observations align with the concept of a spark gap "window" for optimal engine operation. If the gap is too narrow or too wide, combustion quality suffers, albeit for different reasons. Our data empirically confirm the existence of such a window and place it around 0.9–1.0 mm for this particular engine.

It is also instructive to compare how changing the gap parallels other ways of influencing combustion. For instance, retarding ignition timing or EGR can also reduce peak temperatures and NO_x but at a fuel efficiency penalty, somewhat akin to using a smaller gap (leading to cooler, incomplete burns). On the flip side, increasing ignition energy (like using a high-energy ignition coil or multi-spark) could extend the benefits of a larger gap without the misfire drawback – effectively pushing the optimal point further out. Some modern engines and racing applications do run larger gaps (≥1.1 mm) in conjunction with powerful ignition systems to gain a few percentage points of efficiency.

Our results support that approach: if misfires can be avoided, a larger gap clearly improved performance and emissions (CO/HC) up to the point of ignition failure. The synergy between ignition energy and gap is highlighted by [3]: at low ignition energy, a gap of 1.2 mm was unstable, whereas at high energy it was stable. In our case, at the stock energy, 1.2 mm was barely stable and 1.5 mm unstable; a stronger ignition might make 1.5 mm viable and possibly further reduce HC/CO while maintaining low BSFC – likely at the cost of even higher NO_x unless other mitigation is used.

The emissions results also emphasize why regular maintenance of spark plugs (to make sure proper gap) is important. Over time, electrode erosion widens the gap; a plug that erodes from 0.9 mm toward 1.5 mm will gradually cause the engine to experience the symptoms we saw: rising HC/CO emissions, misfire, loss of power, and poor fuel economy. This study quantifies how bad it can get at 1.5 mm – effectively a severely worn plug scenario. It also quantifies the other extreme of a too-narrow gap which might occur if a plug is accidentally gapped incorrectly or if a maladjustment occurs.

The optimal gap delivered the best combination of low fuel consumption and low incomplete combustion products (HC, CO) because of superior flame propagation, whereas suboptimal gaps caused a loss in one or more aspects (either efficiency or emissions or both). The increase of NO_x with improved combustion is expected from the temperature sensitivity of NO_x formation.

Each measurement (BMEP, BSFC, EGT, CO, HC, NO_x) supports the explanation for the others, giving a coherent overall interpretation. We also cross-validated our findings with literature at each step, finding good qualitative and quantitative agreement, which adds confidence that these trends are broadly applicable to SI engines (with potential shifts in the exact optimal gap depending on ignition system strength and engine geometry).

4. Conclusions

This experimental investigation assessed the influence of spark plug gap on engine performance and emissions using a single-cylinder petrol engine, with five discrete gap settings from 0.5 mm up to 1.5 mm. The following key conclusions are drawn, all of which are supported by the observed data and align with prior research:

- Optimal gap for performance: There exists an optimal spark plug gap (around 0.9–1.0 mm in this engine) that maximizes combustion efficiency. At this gap, the engine achieved the highest BMEP (~7.2 bar) and lowest BSFC (~300 g/kWh), corresponding to the best fuel conversion efficiency. Gaps smaller or larger than this optimal caused a decline in performance (up to ~17% lower BMEP and ~27% higher BSFC at 0.5 mm and 1.5 mm gaps) because of suboptimal combustion dynamics. This confirms that proper gap setting is critical for peak engine output.
- Effect of small vs large gaps: A too-small gap (0.5 mm) produced a weak spark that caused slower, prolonged combustion and partial flame quenching. This caused incomplete fuel burn – evidenced by higher CO (2.0%) and HC (~600 ppm) – and a loss of power. A too large gap (1.5 mm) exceeded the ignition system's capability, causing frequent misfires and very erratic combustion. This drastically increased HC (~1000 ppm) and CO (~2.5%) emissions and reduced BMEP. Thus, both extremes caused higher levels of incomplete combustion by different mechanisms (flame quench vs. misfire). The engine operated best in a moderate gap range where the spark was strong enough to ignite the mixture reliably but not so demanding as to fail ignition.
- CO and HC emissions minimization: The study showed that CO and HC emissions can be minimized by using the optimal gap. At 1.0 mm gap, CO dropped to 0.5% and HC to ~300 ppm – roughly half to one-third of the values at the extreme gaps. This underscores that proper spark gapping improves combustion completeness, significantly reducing these harmful emissions. It was shown that deviating from the ideal gap in either direction will raise CO/HC because of less complete combustion.
- NO_x emissions trade-off: NO_x emissions were found to be inversely related to CO and HC with respect to gap changes. The highest NO_x (~2000 ppm) occurred at the 1.0 mm gap where combustion was hottest and most efficient, whereas NO_x was much lower at 0.5 mm and 1.5 mm because of cooler combustion or misfire. This highlights the classic trade-off: optimizing fuel efficiency and low CO/HC tends to increase NO_x due to higher combustion temperatures. Any ignition improvement strategy (like widening gap or increasing spark energy) should therefore consider NO_x mitigation (e.g., via EGR or spark timing adjustments) if necessary.
- Exhaust temperature and energy distribution: As the spark gap was optimized, exhaust gas temperature decreased (580°C at 0.5 mm to 540°C at 1.0 mm) showing more energy converted to work and less wasted as exhaust heat. Extremely large gap caused low EGT (~500°C) primarily because of misfire (unburnt mixture cooling the exhaust). Thus, EGT data corroborate the shift in energy utilization – efficient combustion yields cooler exhaust despite higher internal temperatures, whereas misfire yields cool exhaust because of lack of combustion.
- Consistency with literature: All observed trends – improvement of power and efficiency with increasing gap up to an optimum, U-shaped CO/HC responses, and opposite NO_x behavior – are consistent with previously published experimental studies. This consistency lends validity to the results. It also points to that the findings are generalizable to other SI engines: typically, an optimal gap exists near manufacturer spec, and

significant deviation will hurt performance and/or emissions.

- Practical implications: Maintaining the spark plug at its proper gap is essential for sustained engine performance and emissions compliance. A gap that becomes too wide with wear will cause misfires, increased fuel consumption, and high HC/CO emissions as our 1.5 mm results vividly show. Similarly, using an incorrect (too small) gap setting to "fix" misfires can actually degrade efficiency and is not recommended except to resolve very specific ignition problems. Engine tuners may exploit a slightly larger gap (within the ignition system's capability) to gain efficiency and power, as evidenced by the gains from 0.5→1.0 mm in this study but should monitor for NO_x increases and ensure the ignition energy is sufficient to avoid misfire.

In conclusion, the spark plug gap exerts a significant influence on the combustion process in SI engines. By providing a larger initial flame kernel, a properly widened gap can enhance flame propagation, improve engine efficiency, and reduce incomplete combustion emissions (CO, HC). However, exceeding the ignition system's limits with an overly large gap leads to instability and performance collapse. There is therefore an optimal gap range that yields the best compromise. The experimental results presented in this paper quantify these effects in detail for a single-cylinder engine, reinforcing the importance of ignition system optimization as a means to improve engine performance and emissions. Importantly, the study introduces a quantitative analysis of misfire frequency, strengthening the causal link between gap-induced combustion instability and emission behavior. These results define a practical and experimentally validated spark plug gap range (~0.9–1.0 mm) that balances engine performance with emissions compliance. The findings provide both a methodological advancement and an actionable recommendation for engine designers and calibration engineers seeking to optimize ignition systems under modern emissions constraints. Future work could explore coupling a high-energy ignition source with larger gaps to see if the benefits can be extended without incurring misfire, as well as testing at different engine speeds, loads, and with lean mixtures to map out a full regime of gap effects. In addition, future investigations could benefit from examining the combined effects of spark plug gap size and ignition energy level on combustion performance and emissions. As spark energy demand increases with gap size, a controlled increase in ignition energy may counteract misfire tendencies or extend the stable gap range. Conversely, elevated ignition energy may exacerbate NO_x formation under stoichiometric or lean conditions. A detailed parametric study across a matrix of gap–energy combinations would provide valuable insight into the optimal ignition strategies for advanced SI engine operation. Nevertheless, the trends observed here serve as a valuable guideline for engineers and researchers in understanding and leveraging spark plug gaps as a tunable parameter in engine design and maintenance.

Nomenclature

Symbol	Description
BMEP	Brake Mean Effective Pressure (bar)
BSFC	Brake Specific Fuel Consumption (g/kWh)
EGT	Exhaust Gas Temperature (°C)
CO	Carbon Monoxide (%)
HC	Unburned Hydrocarbons (ppm)
NO_x	Nitrogen Oxides (ppm)
T	Brake Torque (Nm)
N	Engine Speed (RPM)
V_s	Swept Volume or Displacement Volume (m^3)
P_b	Brake Power Output (kW)
$\dot{m}_f$	Fuel Mass Flow Rate (g/h)
λ	Air-Fuel Ratio Equivalence Ratio

CRediT Taxonomy

Ali Can YILMAZ: Investigation, Conceptualization, Supervision, Writing-original draft, Writing-Review & Editing; Ozlem ERDEM YILMAZ: Investigation, Validation, Data curation, Formal analysis

Declaration of Competing Interest

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

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