ANALYSING THE EFFECTS OF TOLUENE PERCENTAGES AND EXHAUST GAS RE-CIRCULATION RATES ON SPARK-IGNITION ENGINE PERFORMANCE AND EMISSIONS

by

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This study delves into the intricate dynamics of gaseous emissions in relation varying parameters in spark-ignition engines: gasoline-toluene blending ratios, exhaust gas re-circulation (EGR) rates, and spark timings. With increasing toluene concentrations, there was a consistent reduction in emissions, culminating in HC values of 67 ppm, CO at 0.6% volume, PM at 11 mg/m³, and NO_x at 100 ppm for a 100% toluene blend. The implementation of EGR demonstrated its efficacy in mitigating NO_x emissions, registering a decline to 60 ppm at a 30% EGR rate. However, the same augmentation in EGR rates witnessed an uptick in HC and CO emissions. Analysis of spark timings pinpointed an optimal advance of 30° CA bTDC at a 50% engine load, yielding minimized emissions. Conclusively, the research underscores the potential of fine-tuning engine parameters, such as fuel composition, EGR rates, and spark advance, to achieve a harmonious balance between engine efficiency and emission reductions. This study lays foundational data for further exploration and optimization in the realm of internal combustion engines.

Key words: *toluene-gasoline blend, EGR rates, spark timing, gaseous emissions, combustion optimization*

Introduction

Spark-ignition engines have shown to be essential in the domain of automobile engineering for transporting cars over long distances. These engines, which are primarily designed to burn petrol, have been the backbone of human mobility for more than a century [1]. Their popularity stems mostly from their efficiency and usability. Although spark-ignition engines have many advantages, they have also produced a variety of pollutants. Aside from the useful energy necessary to propel the vehicle, the undesired byproducts of combustion inside the engine cylinders are ejected into the atmosphere. These emissions have a substantial negative impact on the environment, mostly consisting of HC, CO, NO_x, and PM. Since more people are

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becoming aware of environmental degradation and the effects of GHG, there has been an urgent need to eradicate these pollutants. Engineers and scientists throughout the world are seeking for new ways to meet ever-stricter rules without losing engine performance. In this changing environment, the use of alternative fuels and fuel blends has expanded. Iso-propanol the combination of toluene and petrol is one of these intriguing possibilities. Toluene, a naturally occurring chemical found in crude-oil, possesses qualities that make it a valuable petrol additive [2-4]. The addition of iso-propanol, a common solvent with unique combustion properties, results in a mixture with both potential and challenges. This unique blend may offer improved combustion properties, boosting efficiency and minimising pollutants. Because of the wide range of working conditions, it must first be thoroughly explored before it can be widely utilised and understood [5, 6].

Furthermore, the engine's operating parameters, like the rate of EGR, can further modulate these effects. The EGR, a technique used in internal combustion engines, involves recirculating a portion of an engine's exhaust gas back to the engine cylinders. This not only dilutes the incoming air, thereby reducing peak cylinder temperature and NO_x formation but also affects other emission parameters. Thus, understanding the interplay between Toluene percentages and EGR rates becomes paramount. How do they jointly affect the engine's performance and emissions. Are there optimal conditions that maximize performance while minimizing harmful emissions. These are just some of the pertinent questions that need answers [7, 8]. It's imperative, therefore, to delve into the dynamics of spark-ignition engines powered by iso-propanol toluene/gasoline blends. By analysing the effects of toluene percentages and EGR rates on engine performance and emissions, we can pave the way for a cleaner, more efficient future for automotive propulsion, harmoniously blending the demands of performance with the imperatives of environmental responsibility.

The world of spark-ignition engines has been extensively documented, with countless studies offering insights into their operations, efficiencies, and emissions. Over the decades, researchers have grappled with the challenge of balancing engine performance with environmental sustainability, with various fuel blends and technologies emerging as potential solutions. Historically, gasoline has been the primary fuel for spark-ignition engines. But as a study [9] illustrated, while gasoline's chemical and physical properties make it an ideal fuel for these engines, its combustion inevitably leads to harmful emissions. Their extensive work highlighted [10, 11] the primary pollutants produced by these engines and the environmental and health consequences associated with them. This foundational research set the stage for the quest for alternative fuels and fuel blends. In the alternative fuels landscape, toluene has been studied for its potential benefits and challenges. A study [12] was among the earliest to explore the combustion properties of toluene when used as an additive in gasoline. They identified that toluene could enhance the octane number of gasoline, leading to smoother combustion and reduced knocking. However, they also pointed out that, in higher concentrations, toluene could lead to increased emissions of unburned hydrocarbons [13-17].

The synergy between iso-propanol and toluene as a combined gasoline blend is a relatively newer area of exploration. Preliminary studies, indicated that this unique blend could offer significant reductions in NO_x emissions while marginally improving engine efficiency. These work was pivotal in highlighting the value of understanding the optimal blending ratios to achieve desired outcomes [14, 15, 18]. Another pivotal aspect of engine operations that has garnered attention is the EGR technique. Its origins can be traced back to a work, which [19] highlighted EGR as a tool for reducing peak combustion temperatures and consequently, NO_x emissions. The principle is simple: by re-circulating a portion of the exhaust gases back into the engine, the combustion temperature is moderated, leading to reduced NO_x formation. However, the effects of EGR are multifaceted. As a study [20] the impact of the laminar flame speed correlation on the prediction of the combustion process and performance of a gasoline engine is investigated using a 1-D numerical approach. The model predictions are compared with experimental data available for full- and part-load operations of a small-size naturally aspirated spark-ignition (spark-ignition demonstrated, while EGR effectively reduces NO_x emissions, it can increase other emissions, notably HC and PM, especially when used with certain fuel blends [21, 22]. The interplay between toluene percentages, iso-propanol, and EGR rates in spark-ignition engines is a burgeoning field. While individual studies have shed light on specific aspects, a comprehensive understanding requires an integrated approach. This is further complicated by the myriad of engine configurations and operating conditions under which these studies were conducted. The research has so far stressed the importance of conducting intricate, situation-specific analyses in order to identify the engine operation parameters that are the most effective and ecologically benign.

Experimental set-up

As shown in fig. 1, the experiments for this study used a cutting-edge spark-ignition engine to analyse the impact of various fuel blends and engine operation parameters on emissions and performance. The one-cylinder, 4-stroke engine was designed primarily for research purposes and offers adaptability in terms of changing operational conditions, tools, and measuring capabilities. This architecture allows for close observation and research of the combustion process's delicate aspects. The air-fuel ratio may be carefully adjusted thanks to the engine's direct injection mechanism. This feature is critical for evaluating the effects of various fuel blends since it promotes more efficient and uniform combustion. The engine's electronic control unit (ECU) is also adaptable, allowing alterations to ignition timing, injection length, and other critical aspects for the study's objectives.

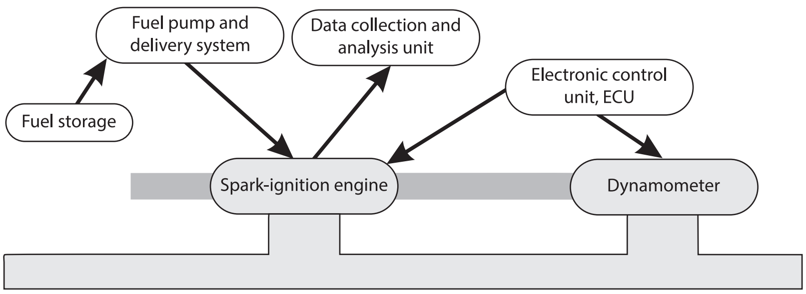

Figure 1. Experimental set-up

An integral part of the engine design is the sophisticated sensor array that this engine employs to continuously monitor crucial parameters like in-cylinder pressure, exhaust gas composition, and temperature. Real-time data from these sensors is essential for comprehending the mechanics of combustion, particularly while modifying the toluene concentrations and EGR rates. For research purposes, the engine's cooling system has also been improved. It uses a liquid cooling system to maintain consistent engine temperatures throughout the testing in order to decrease the impact of outside influences on the combustion process. With this level of regulation, it is guaranteed that any reported changes in emissions or performance are due to modifications to the fuel blend and EGR rates rather than shifts in the ambient temperature. The following tab. 1 offers a thorough analysis of the engine's specifications for a greater understanding.

Table 1. Engine specification

Specification	Details
Engine type	Single cylinder, four-stroke
Displacement	500 cc
Bore × stroke	86 mm × 86 mm
Compression ratio	10.5:1
Fuel injection	Direct injection
Ignition system	Electronic spark ignition
Cooling system	Liquid cooled
Maximum power	34 kW at 6500 rpm
Maximum torque	45 Nm at 5500 rpm
Exhaust system	Equipped with EGR and gas composition sensors
Sensors	In-cylinder pressure, exhaust gas temperature, O_2 concentration, *etc*.
Control unit	Adjustable ECU

Fuel blends

The type of fuel utilised in an engine arrangement has a significant impact on combustion and emissions. The exploratory toluene and petrol mixes drew a lot of interest. These mixtures were meticulously developed to provide a range of toluene concentrations, each with its own set of properties that influence combustion behaviour. Toluene is an aromatic chemical found naturally in crude-oil and is commonly found in petrol. Because it has a higher octane rating than regular fuel, it is more likely to have anti-knock properties. Petrol, on the other hand, is a complex blend of HC with varying chain lengths and structural properties. To improve their excellent combustion powers, toluene and petrol are mixed. Petrol has a lot of energy and is highly elastic.

To meet the study's objectives, a variety of mix ratios were created, ranging from pure petrol to blends containing traces of toluene. Using this procedure, it was feasible to determine how the presence of toluene affects combustion and emissions. This method can also be used to estimate the optimal mix ratio for balancing emissions, efficiency, and performance. The tab. 2 clearly describes the critical toluene and petrol properties that impact how the blends work.

Table 2. Blend properties

Property	Gasoline	Toluene
Molecular formula	C_4-C_{12} (varies)	C_7H_8
Boiling point [°C]	30-200 (depends on fraction)	110.6
Density [kgm^{-3}]	720-775	866
Octane number	85-98 (depends on grade)	112
Lower heating value [MJkg^{-1}]	44.0	40.1
Vapor pressure [kPa]	Varies with temperature	3.79 (at 20 °C)
Viscosity [cP]	0.4-0.8	0.590
Flash point [°C]	< –40	4.4

This table lists the various properties of petrol and toluene. How these qualities are distributed throughout the fuel determines how it responds to burning. To adequately grasp the benefits and challenges offered by toluene/gasoline combinations in spark-ignition engines, it is critical to understand how these features truly translate in actual engine performance and emission profiles.

Experimental procedure

The primary purpose of this research was to understand how toluene/gasoline mixtures react in spark-ignition engines, particularly in terms of emissions. To collect all of the data, an exact and complete experimental protocol was established. First, the engine must be readied. For optimal performance, the engine must be in perfect working order and clear of residue.

To ensure there were no leftovers from previous tests, the engine was readied for the toluene/gasoline tests with a series of runs using only pure petrol. The engine was started with the initial toluene/gasoline mixture, which contained the least amount of toluene. The engine was driven for a predetermined amount of time to achieve a steady operating temperature. During this time, the engine's operational characteristics, such as load, spark timing, and EGR rate, were often adjusted to meet the experimental design. To track contaminants, modern exhaust gas analyzers were fitted in the engine's exhaust system. This extremely exact method was used to quantify important pollutants such as NO_x, CO, HC, and PM in real time. The engine also had sensors that monitored pressures, temperatures, and other critical characteristics. The study's dual data gathering technique was used to obtain performance and emissions data for each test scenario. Following data collection, the procedure was repeated while the engine was being fueled with the resulting toluene/gasoline mixture. Because each combination was carefully examined in line with a specified protocol, the results were dependable and consistent. The importance of uniformity during the testing process cannot be overstated. Each test scenario for each blend was repeated multiple times to account for any abnormalities and to ensure the veracity of the results. Table 3 summarises the testing procedures employed in this investigation.

Table 3. Testing methods

Testing Method	Description
Engine priming	Preliminary runs with pure gasoline to condition the engine for testing
Blend introduction	Sequential introduction of blends, starting from the lowest Toluene concentration
Operational variations	Varying engine parameters such as load, spark timing, and EGR rate
Emission analysis	Real-time capture of gaseous emissions using an exhaust gas analyzer
Performance monitoring	Real-time monitoring of in-cylinder pressures, temperatures, and other parameters
Repeatability tests	Each blend and scenario repeated multiple times for consistency

As part of the experimental strategy, each toluene/gasoline mixture was subjected to rigorous testing. Toluene has both potential and limitations in spark-ignition engines, and this study aimed to combine systematic engine operating adjustments with real-time data collection on both performance and emissions.

Result and discussion

Maximum brake torque timing

One of the pivotal parameters in engine performance is the timing at which maximum brake torque (MBT) is achieved. This timing represents the optimal ignition advance that yields the highest torque from the engine. With the introduction of toluene in varying proportions, there were notable shifts in the MBT, reflecting the altered combustion dynamics of the blended fuel.

To provide a clear and concise picture of the observed trends, results were tabulated for different blending ratios of toluene with gasoline. The tab. 4 showcases the correlation between the blending ratio and the corresponding MBT value. It is evident from the table that as the proportion of toluene increases in the blend, there's a corresponding shift in the MBT towards earlier crank angles. This suggests that the combustion properties of toluene cause it to achieve maximum torque at slightly advanced ignition timings compared to conventional gasoline. This shift in MBT timing is crucial for engine calibration and optimal performance when using toluene blends. Understanding this relationship aids in optimizing spark advance settings, ensuring that engines can harness the full potential of the fuel while minimizing harmful emissions.

For engines, the load plays a pivotal role in influencing various performance parameters, including the MBT. As load changes, the amount of air and fuel entering the cylinder varies, which subsequently affects combustion dynamics. For our study, with a specific blending ratio (x = 10), an EGR rate of 0, and an excess air ratio, λ, set to 1.0, the MBT timings were observed across various engine loads. The tab. 5 below provides a synthesized overview of the MBT timings at different loads for the given conditions.

Table 4. Blending ratio and MBT

Blending ratio (toluene: gasoline)	MBT [°CA bTDC]
0:100 (pure gasoline)	12°
10:90	11.5°
20:80	11°
30:70	10.8°
40:60	10.5°
50:50	10°
60:40	9.8°
70:30	9.5°
80:20	9°
90:10	8.5°
100:0 (pure toluene)	8°

Table 5. The Load *vs.* MBT

Load, L, [% of max load]	MBT [°CA bTDC]
10%	13°
20%	12.5°
30%	12°
40%	11.7°
50%	11.5°
60%	11°
70%	10.8°
80%	10.5°
90%	10°
100% (full load)	9.5°

The data illustrates that as the engine load increases, the MBT timing tends to advance, which means it occurs earlier in the combustion cycle. This behavior can be attributed to the increased in-cylinder pressures and temperatures at higher loads, accelerating the combustion process. The results, under the given conditions, present valuable insights for engine calibration, especially when considering the integration of toluene in the fuel blend. Properly adjusting the spark advance as per the load conditions will ensure efficient combustion, maximizing power output, and reducing undesirable emissions.

Effect of load on gaseous emissions

The relationship between engine load and gaseous emissions is both intricate and fundamental to the field of internal combustion engines. As the engine operates under different loads, the combustion environment within the cylinder undergoes changes. These changes, in turn, impact the formation and release of various emissions. During this study, as the load increased, notable variations were observed in the emissions of HC, CO, PM, and NO_x.

The HC are unburned or partially burned fuel. Their emissions tend to be higher at lower loads due to incomplete combustion. This is primarily because at lower loads, the combustion temperature is relatively lower, leading to less efficient fuel burn. The CO emissions, which result from incomplete combustion of carbon in the fuel, showcased a similar trend to HC. Lower loads, which correlate with cooler combustion temperatures and leaner mixtures, can lead to elevated CO emissions. The NO_x on the other hand, behave differently. These compounds form when the nitrogen in the air reacts with oxygen under high temperatures. Thus, as the engine load increases, in-cylinder temperatures rise, leading to higher NO_x emissions. Lastly, PM mainly consists of tiny particles formed from unburned fuel, lubrication oil, and other compounds. The PM emissions showed an increased trend with rising load, reflecting the complexities of combustion dynamics under high pressures and temperatures.

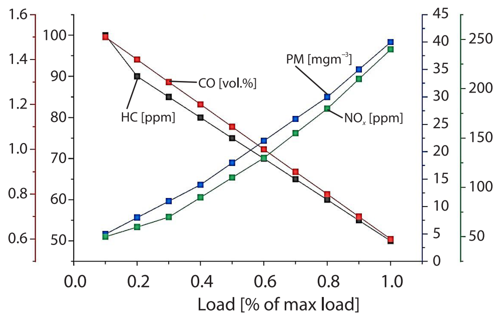

Figure 2. Effect of load on gaseous emissions

The intricate dynamics between engine load and gaseous emissions are evidently reflected in the data gathered during the study as displayed in previous fig. 2. As the engine operates under varying loads, the combustion environment undergoes significant shifts, influencing the formation and release of several emissions such as HC, CO, PM, and NO_x. The HC, representing unburned or partially burned fuel, show a declining trend with increasing engine load. At lower loads, incomplete combustion, due to relatively cooler temperatures, results in elevated HC emissions. This behavior is evident from the data, where HC levels started at 100 ppm at 10% load and gradually decreased to 50 ppm at full load. A similar pattern is observed with CO emissions. The CO, emerging from incomplete combustion of carbon in the fuel, is higher at lower loads where combustion temperatures are cooler and mixtures leaner. The data indicates a decline from 1.5% volume at a 10% load to 0.6% volume at a 100% load. Conversely, NO_x demonstrate an opposite behavior. The NO_x emissions are attributed to the reaction between nitrogen and oxygen in the air, a reaction that is enhanced at higher temperatures. As engine load increases, and subsequently the in-cylinder temperatures rise, NO_x emissions follow suit. The values leap from 50 ppm at a 10% load to a significant 240 ppm at full load. The PM emissions also manifest an increasing trend with the engine load. Comprising tiny particles formed from elements like unburned fuel and lubrication oil, PM emissions amplify as combustion dynamics become complex under heightened pressures and temperatures. This progression is clear in the data, with PM levels starting at 5 mg/m³ at 10% load and escalating to 40 mg/m³ at full load. This data accentuates the nuances of combustion and the resulting emissions, especially under varied operational conditions. These findings not only provide insights into the behavior of specific emissions across different loads but also emphasize the importance of efficient combustion management. By fine-tuning engine parameters, such as spark timing or air-fuel ratio, there's potential to optimize these emissions, ensuring engines are both powerful and environmentally considerate.

Effect of spark timings on gaseous emissions

Spark timing, or the exact moment when the spark plug ignites the air-fuel mixture in the combustion chamber, is a pivotal parameter affecting the engine's combustion dynamics. By altering spark timings, one can significantly affect the combustion efficiency, peak temperatures, and subsequently, the emissions. In our study, we investigated how varying spark timings influence gaseous emissions of HC, CO, PM, and NO_x, specifically at a 50% engine load.

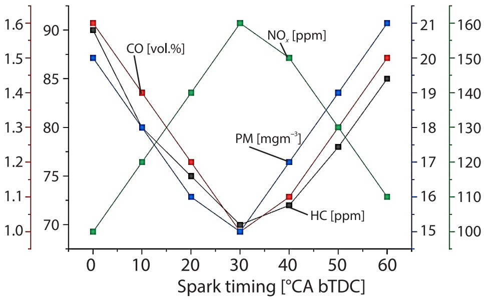

Figure 3. Effect of spark timing on gaseous emissions

The exploration into the effects of spark timing on gaseous emissions provides rich insights into combustion dynamics, particularly at an intermediate engine load of 50% is shown in fig. 3. The data reveals nuanced patterns across varying spark timings, and each emission type responds distinctly to these alterations. The HC, representative of unburned or partially combusted fuel, exhibit an interesting trend. As spark timing advances to around 30° CA bTDC, HC emissions decline, indicating a more complete combustion. This makes sense as advancing the spark gives the air-fuel mixture more time to burn, leading to better combustion efficiency. However, post this optimal point, there's a noticeable uptick in HC emissions, emphasizing the detrimental effects of excessively advanced timings, which can lead to incomplete combustion or even engine knocking.

The CO emissions, a direct consequence of incomplete combustion, follow a trajectory akin to HC. Initially, with the advancement of spark timing, there's a reduction in CO emissions, reaching a low at 30° CA bTDC. This suggests that the combustion process benefits from the additional time available, leading to reduced formation of CO. However, beyond this optimal spark advance, CO levels rise, emphasizing the risks of suboptimal combustion. The NO_x present a different narrative. The NO_x formation is tied to high combustion temperatures and pressures. In the early phases of advancing the spark timing, NO_x emissions increase, peaking around 30° CA bTDC. This indicates that the advanced timing leads to elevated temperatures and pressures conducive for NO_x formation. However, further advancing the timing results in reduced NO_x emissions, possibly due to the onset of engine knocking or overly advanced combustion leading to cooler overall combustion temperatures. Lastly, the data on PM highlights its intricate relationship with combustion dynamics. The PM emissions fluctuate across the range of spark timings. There's a decrease initially, reaching a minimum around 30° CA bTDC, post which the emissions increase again. This behavior suggests that PM formation is not just tied to incomplete combustion but also to the specific temperature and pressure profiles within the combustion chamber. In essence, the data underscores the delicate balancing act involved in engine calibration. While there's a discernible sweet spot in spark timing that optimizes emissions, straying too far from this point in either direction can lead to increased pollutant formation. This emphasizes the need for precision in tuning engine parameters to ensure optimal performance while keeping emissions in check.

Effect of EGR rate on gaseous emissions

The practice of integrating EGR into internal combustion engines offers profound insights into the modulation of gaseous emissions. The EGR operates by reintroducing a portion of the engine's exhaust gas back into the combustion chambers. This process inherently dilutes the air intake, which, in turn, impacts the oxygen concentration and modulates combustion temperatures. The fig. 4 data provides an intriguing glimpse into how different EGR rates influence the levels of various pollutants. Starting with HC.

Their presence typically denotes unburned or partially combusted fuel. As the data reveals, as EGR rates ascend, there's a concomitant increase in HC emissions. This can be attributed to the cooling effect of the EGR. A cooler combustion chamber can sometimes lead to less efficient burning, translating into elevated HC levels. Parallelly, CO which emerges from incomplete combustion, also sees a similar uptick with rising EGR rates. The rationale behind this can be linked to the EGR's reduction of available oxygen for combustion. As oxygen levels dip, it results in less effective oxidation of the fuel, manifesting as heightened CO emissions. In stark contrast, NO_x show a different behavior. These emissions are tightly bound to the temperature dynamics within the combustion chamber. Given that EGR introduces a cooling mechanism by displacing some of the oxygen, the resultant dilution causes a marked reduction in NO_x emissions. This cooling effect diminishes the conditions necessary for NO_x formation, which requires high temperatures. The data distinctly showcases this trend, with NO_x levels plummeting as EGR rates rise. Lastly, the behavior of PM under varying EGR rates paints a complex picture. The PM levels escalate with increasing EGR. This can be associated with the relatively cooler combustion conditions and potential pockets of incomplete combustion, both of which can foster the formation of particulates. In synthesizing the data, it becomes apparent that the integration of EGR into engine systems is a double-edged sword. While it offers the boon of significantly reducing NO_x emissions, it presents challenges in the form of elevated HC, CO, and PM levels. Balancing these aspects is crucial, necessitating precise calibration and optimization strategies to harness the benefits of EGR while curtailing its drawbacks.

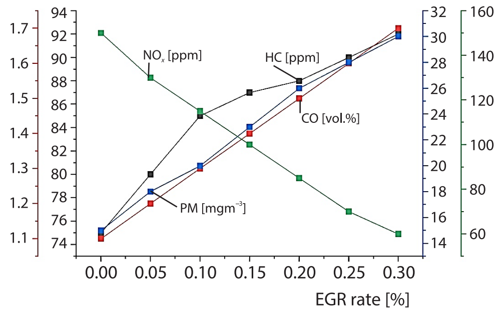

Figure 4. Effect of EGR rate on gaseous emissions

Effect of blending ratio on gaseous emissions

The data obtained from experimenting with different blending ratios of gasoline to toluene illuminates the intricate interplay between fuel composition and gaseous emissions. Toluene, known for its unique combustion characteristics, when blended with gasoline, presents an array of results that are both intriguing and informative. When examining HC, these emissions largely represent unburned or partially burned fuel. The fig. 5 data suggests a gradual decrease in HC levels as the toluene content in the blend escalates. This can be attributed to toluene's superior anti-knock properties and its higher octane number. Such properties potentially lead to a more comprehensive combustion process, minimizing the amount of unburned fuel remnants. The CO emissions, indicative of incomplete combustion, also showcase a downward trend with increased toluene concentrations. Given the combustion nuances of toluene, it's conceivable that the fuel's combustion is more complete or efficient compared to standard gasoline, leading to reduced CO generation. The behavior of NO_x offers deeper insights. These emissions are closely tied to the peak temperatures attained during combustion. As the figure suggests, NO_x levels decline with rising toluene content. This might seem counterintuitive, given that toluene's higher octane could be associated with higher combustion temperatures. However, the observed reduction indicates that while toluene might alter the combustion dynamics, it does not necessarily push temperatures to levels that would enhance NO_x formation. Lastly, PM emissions present a particularly compelling narrative. The data indicates a consistent reduction in PM levels with increasing toluene content. This suggests that toluene, aside from influencing the gaseous emissions, also impacts the particulate byproducts of combustion. The reduction in PM might be tied to more efficient combustion or altered temperature and pressure profiles influenced by toluene. In summation, the influence of toluene on the combustion process and resultant emissions underscores the potential of custom fuel formulations. By adjusting the blend of gasoline and toluene, it's conceivable to achieve not only optimal engine performance but also a reduction in detrimental emissions. The data serves as a testament to the significance of fuel composition in shaping a more sustainable and efficient combustion landscape.

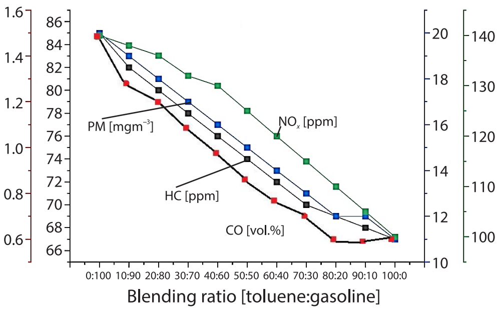

Figure 5. Effect of blending ratio on gaseous emissions

Conclusion

The investigation into the effects of varying fuel parameters, specifically blending ratios of gasoline to toluene, EGR rates, and spark timings, offers pivotal insights into combustion dynamics and resultant gaseous emissions. A clear pattern emerges: toluene, with its unique combustion properties, when introduced in increasing proportions, consistently reduces HC, CO, PM, and NO_x emissions. At a 100% toluene blend, HC emissions dip to 67 ppm, CO stands at 0.6% volume, PM reduces to 11 mg/m³, and NO_x drops to 100 ppm. The EGR rates further elucidate the emission landscape, with NO_x levels plummeting to 60 ppm at a 30% EGR rate, underscoring its effectiveness in curbing NO_x. However, increasing EGR rates also amplify both HC and CO emissions, revealing a challenge in optimizing all emission parameters concurrently. The interplay of spark timing too cannot be understated. At a 50% engine load, an optimal spark advance around 30° CA bTDC minimizes most emissions. In conclusion, through precise calibration and understanding the multifaceted relationship between fuel formulation, EGR rates, and spark timing, it's evident that achieving both optimal engine performance and reduced emissions is a tangible objective.

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