The gasoline fuel quality impact on fuel consumption, air-fuel ratio (AFR), lambda (λ) and exhaust emissions of gasoline-fueled vehicles

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Abstract: Improving the gasoline fuel combustion, reducing gasoline fuel consumption and reducing vehicles exhaust emissions pollution associated with gasoline combustion become growing interest locally and global-wide. To satisfy the exhaust gas emissions rules and regulations and reducing fuel consumption, it is very significant and critical to determine and understand the gasoline fuel quality impact on fuel consumption, air-fuel ratio (AFR), lambda (λ) and exhaust emissions of gasoline-fueled vehicles. Therefore, studying the impact of gasoline fuel quality on fuel consumption, the air-fuel ratio (AFR), lambda (λ) and exhaust emissions of gasoline-fueled vehicles is very important and necessary. A sensitive and detailed analysis conducted to analyze and determine the impact of gasoline fuel quality on fuel consumption, air-fuel ratio (AFR), lambda (λ) and exhaust emissions of gasoline-fueled vehicles. The study results indicated a direct impact of gasoline fuel quality on fuel consumption, the air-fuel ratio (AFR), lambda (λ) and some vehicle exhaust gases emission including carbon dioxide (CO2), oxygen (O2) and nitrogen oxides (NOx). Also, the results indicated the indirect impact of gasoline fuel quality on hydrocarbons (CxHy) vehicle exhaust emission. The results of this study can help in reducing fuel consumption, improving the quality of fuel combustion and reducing vehicle exhaust emissions.

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PUBLIC INTEREST STATEMENT
Gasoline, also called petrol or gas, a mixture of volatile, flammable liquid hydrocarbons derived from crude oil and used as fuel for internal combustion engines. Gasoline used in automobiles boils mainly between 30°C and 200°C, the blend or mixture being adjusted to altitude and season. Improving the gasoline fuel combustion, reducing gasoline fuel consumption and reducing vehicles exhaust emissions pollution associated with gasoline combustion become growing interest locally and global-wide. To satisfy the exhaust gas emissions rules and regulations and reducing fuel consumption, it is very significant and critical to determine and understand the gasoline fuel quality impact on fuel consumption, air-fuel ratio (AFR), lambda (λ) and exhaust emissions of gasoline-fueled vehicles. Therefore, studying the impact of gasoline fuel quality on fuel consumption, the air-fuel ratio (AFR), lambda (λ) and exhaust emissions of gasoline-fueled vehicles is very important and necessary.
1. Introduction

With growing concerns about the contribution of transportation sector’s to climate change, many vehicle manufacturing companies are looking to deploy high compression and more efficient engines that have greater fuel economy and emit less carbon dioxide (CO2). To date, however, the use of high compression engines has been obstructed by the low gasoline octane rating. This increases the possibility of engine knock, wherein gasoline self-ignites and explodes, reducing vehicle efficiency and performance. In order to overcome this issue, vehicle manufacture companies have called on the US Environmental Protection Agency (EPA) to adopt regulations to increase levels of gasoline octane. While EPA officials have previously expressed support for regulation, it is not clear if an action will be taken by the Trump Administration. In the absence of federal action, states may wish to adopt their own regulations (Webb, 2017).

The quality of Australian fuel affects the quantity and type of emissions from Australian vehicles. It, directly and indirectly, influences the quality of the breathing air and the amount of greenhouse gas in the environment. Improving Australia’s fuel standards would enable vehicles and their emission control systems to operate effectively and facilitate the adoption of better engine and emission control technologies. To reduce the impacts of noxious vehicle emissions, Australia has historically adopted increasingly stringent European vehicle emissions standards. In October 2015, the Australian Government established the Ministerial Forum on Vehicle Emissions to coordinate a whole-of-government approach to reducing motor vehicle emissions that harm the health and contribute to greenhouse gas emissions.

As part of this work, the Ministerial Forum is considering three measures:

- Euro 6/VI vehicle emissions standards to reduce noxious emissions.
- Fuel efficiency standards to reduce carbon dioxide emissions.
- Fuel quality standards and instruments to reduce noxious and greenhouse gas emissions.

Noxious vehicle emissions (those that are harmful to the health) include carbon monoxide (CO), nitrogen oxides (NOx), volatile organic compounds (VOCs), particulate matter (PM) and sulfur dioxide (SO2) (Department of the Environment and Energy, 2018).

The sulfur levels of petrol supplied to the Australian market are a critical parameter in estimating the environmental benefits of changing the fuel standard for petrol. Sulfur levels of fuel currently supplied to the Australian market are considerably below the parameters specified in the Fuel Quality Standards Act (FQSA). Failure to recognize this fact will lead to a significant over-estimate of the environmental benefits. Moreover, it is important that the motor vehicle industry takes the market quality of fuel into consideration when determining whether vehicles can operate on Australian fuels (Australian Institute of Petroleum (AIP), 2017).

Fuel quality has a direct link to the emissions from vehicles. During the discussion in a task force meeting, it was agreed that if National Capital Territory (NCT) of Delhi can move to BS–VI compliant fuels without any change in current vehicle technology, it would be beneficial to improving the air quality of Delhi. The BS–VI fuel offers significant advantages compared to BS–IV fuel being used today including reduced sulfur (80% reduction) content and reduced polycyclic aromatic hydrocarbon (PAH) (27% reduction) content (Confederation of Indian Industry (CII) and NITI Aayog, 2018).
Motor vehicles have helped shape the world we live in and enabled freedom of movement and economic growth. The burning of fossil fuels does emit carbon and other emissions. Carbon emissions impact on climate change, while other emissions (including pollutants such as NOx and PM) impact air quality, at a local rather than the national level. The automotive sector is committed to reducing both pollutant and CO2 emissions from vehicles, improving the sector's environmental impact is a strategic priority and spends more than 5% of its turnover on research and development (THE SOCIETY OF MOTOR MANUFACTURERS AND TRADERS, 2018).

The world has over 1.5 billion motor vehicles today, and that number is projected to exceed 2 billion by 2020. The transport sector consumes about 48 million barrels of oil per day, against current global oil consumption of 93 million barrels of oil per day (U.S. Energy Information Administration, 2014). More than 50% of global oil production goes to the fuel consumed by the transport sector (Figure 1), which is almost completely powered by oil (Kodjak, 2015).

In 2010, almost 25% of all anthropogenic carbon dioxide (CO2) emissions, 8.8 Gigatons, produced by the global transport sector (Figure 2) (Global Transportation Energy and Climate Roadmap, 2012). Within the transport sector, road transport accounted for about three quarters of fuel consumption and carbon dioxide (CO2) emissions (6.5 Gigatons) (Kodjak, 2015).

Increased levels of air pollution in major urban areas such as Los Angeles and London in the first half of the 20th century led atmospheric scientists to identify vehicle exhaust emissions as an important and significant contributor. The first vehicle exhaust emission standards were established in California and the United States in the late 1960s to address increased levels of smog. Over the course of the second half of the 20th century, three major regulatory programs have been developed in Europe, the United States, and Japan. More strict emission standards were adopted as the understanding of the effects of pollution on public health and the environment and the science of air pollution, improved over time. In the 1970s and 1980s, the first world fuel economy standards established in the United States and Japan. Vehicle manufacturers were required to manufacture new passenger vehicles with lower fuel consumption and increased energy efficiency. In the 1990s, Europe established voluntary carbon dioxide (CO2) standards for passenger vehicles that also required vehicle manufacture companies to improve the fuel efficiency of new vehicles. Since the only way to reduce carbon dioxide (CO2) vehicle exhaust emission is to improve the fuel efficiency of the vehicle, fuel economy and carbon dioxide (CO2) standards interchangeable are considered (Kodjak, 2015).

**Figure 1.** The global oil consumption by sector in 2010 (Sieminski, 2014).
Today, Europe and Japan are home to the world’s most efficient passenger vehicles, and Europe’s 95 g CO2/km is designated the world-class emission standard. Similarly, the United States has adopted the world’s most transformational fuel economy standards, which will double the fuel economy of new passenger vehicles by 2025. To date, the United States is the only nation that has achieved the Global Fuel Economy Initiative's target of doubling the fuel economy of a new passenger vehicle by 2030 (GFEI, 2015).

The U.S. Department of Energy’s (DOE’s) Co-Optimization of Fuels & Engines (Co-Optima) initiative is conducting the early-stage research and development needed to accelerate the market introduction of advanced fuel and engine technologies. The research includes both spark-ignition (SI) and compression-ignition combustion approaches as well as a multi-mode operation that includes combinations of SI and compression-ignition combustion approaches. Target applications include the entire on-road fleet (light, medium, and heavy-duty vehicles). The initiative’s major goals include (Farrell, Holladay, & Wagner, 2018):

1. Improving light-duty vehicle fuel economy 10% beyond the projected results of existing research and development efforts, which when combined represent a total improvement of more than 35% in relation to a 2015 baseline;
2. Improving heavy-duty fuel economy by up to 4%, representing up to $5 billion savings in annual fuel costs;
3. Providing the market pull for up to 25 billion gallons/year of domestically sourced fuel;
4. Identifying lower-cost pathways to reduce emissions; and
5. Leveraging diverse U.S. fuel resources.

Fuel consumption is an ongoing expense and should be considered when leasing or purchasing a vehicle. Selecting the appropriate size of vehicle and most fuel-efficient, using the vehicle only when needed, driving in a fuel-efficient manner and following the manufacturer’s operation and maintenance recommendations for the vehicle can save fuel and money year after year even more if fuel prices rise. The choices of buying a vehicle and how drive it also has a significant impact on the environment and public health. Greenhouse gases (GHGs), mainly carbon dioxide (CO2), are produced when fuel is burned in the vehicle’s engine. Carbon dioxide (CO2) emissions are directly proportional to the amount of fuel consumed for every liter of gasoline used; about 2.3 kilograms
(kg) of carbon dioxide (CO2) is generated. Although not directly harmful to public health, carbon dioxide (CO2) emissions contribute to climate change (Natural Resources Canada, 2017).

The Australian Automobile Association (AAA) supports changing Australia’s fuel quality standards to reduce air pollution produce by vehicles exhaust emissions and ensure appropriate fuels are available to support new engine technologies into future vehicles. In fact, without the availability of appropriate fuel specifications and standards, the Government is unlikely to achieve its target of desired health benefits from noxious emission standards and carbon dioxide (CO2) emission reduction targets from the light vehicle (LV) fleet. However, the Australian Automobile Association (AAA) believes the timeline for the introduction of new fuel quality standards must be based on when there will be adequate availability of appropriate fuels to meet demand, so avoiding price shocks to the Australian fuel market. The Australian Automobile Association (AAA) believes any changes to fuel quality standards and their timing support the Government’s ability to introduce Euro 6 and a carbon dioxide (CO2) standard for new cars. This is because implementation timelines for carbon dioxide (CO2) and especially Euro 6 standards are to a large extent dependent on what fuel is available in the Australian market and when. It is difficult or hard to form a view on timelines for introducing these emission standards without the government first signaling its intention regarding fuel quality standards (Australian Automobile Association, 2017).

The transport sector accounts are responsible for 17% or 92 million tons carbon dioxide (CO2) of Australia’s emissions between 2013 and 2014, with passenger and light commercial vehicles contributing 62% of the sector’s total emissions. As a signatory to the Paris Agreement, Australia committed to the global transition to zero emissions, requiring or demanding the development of long-term decarbonization strategies. Australia has proposed an economy-wide target to reduce greenhouse gas emissions by 26% to 28% below 2005 levels by 2030. This includes the investigation of opportunities to improve the vehicle’s efficiency, with an estimate of 100 million tons carbon dioxide (CO2) emissions reduction between 2020 and 2030 identified (ClimateWorks Australia and Future Climate Australia, 2016).

Climate change is widely viewed as the most important long-term risk to the global environment as well as a substantial risk and threat to public health. Human produced emissions of greenhouse gases (GHGs) are the main cause of most of the observed global warming over the last 50 years and into the future. Burning and consuming fossil fuels such as gasoline and diesel releases greenhouse gases (GHGs) into the atmosphere, contributing to global climate change. Road transport accounts for about 23% (1.7 billion tons) of the United States greenhouse gases (GHGs) emissions each year. The average recent model vehicle emits 6 to 9 tons of exhaust emission gases each year, most of which is CO2. Unlike other types of vehicle pollution, CO2 emissions cannot be reduced by pollution control technologies. They can only be reduced by consuming less fuel or by consuming fuel that contains less carbon (EPA and DOE, 2017).

In 2004, a group of vehicle manufacturing companies created the TOP TIER™ Detergent Gasoline program to develop a higher standard for gasoline fuel detergent additives that better protects against general carbon buildup and intake valve deposits. Aside from the Environmental Protection Agency’s (EPA’s) lowest additive concentration mandate, the TOP TIER™ Detergent Gasoline program is the only performance standard for gasoline fuel deposit control performance (American Automobile Association, 2016).

The Environmental Protection Agency (EPA) has established carbon dioxide (CO2) emissions standards for the model year 2012 through 2025 light-duty vehicles (LDV). Research by the Environmental Protection Agency (EPA) and the Department of Transportation suggests that those standards can be accomplished through improvements in engine design without any change in fuels. This has, however, been disputed by some vehicle manufacturing companies who claim that an increase in fuel octane levels is necessary to achieve the standards at low cost (Webb, 2017).
2. Literature review

A new four-stroke carburetor motorcycle engine without any engine adjustments was used to study the impact and influence of gasoline fuel aromatic content on exhaust emissions of criteria air pollutants (carbon monoxide (CO), total hydrocarbons (THC), and nitrogen oxides (NOx)). Three aromatic gasoline fuels were tested, containing 15%, 25%, and 50% (volume) aromatics mixed with gasoline. A commercial unleaded gasoline fuel was also tested as a reference case (RF). The experimental data indicated that a lower aromatic content (25 and 15 volume%) in gasoline fuel reduced the amounts of total hydrocarbons (THC) and nitrogen oxides (NOx) by more than 10% compared to the reference gasoline fuel (aromatic content 30 volume%). Carbon monoxide (CO) emissions, on the other hand, did not appear to be related to the aromatic content of gasoline fuel. The excess air ratio or lambda (λ) values for the aromatic gasoline test fuels were lower than 1.0, i.e., under rich air-fuel ratio conditions, and carbon monoxide (CO) emissions increased due to lack of oxygen. In contrast, high nitrogen oxides (NOx) emissions appeared in a near stoichiometric air-fuel ratio (AFR) and decreased as the fuel mixture approached lean or rich conditions. The results also showed that decreasing the aromatic content from 50 to 25 and 15 volume% in gasoline may result in a reduction of benzene emissions from the motorcycles without a catalyst converter. The study showed that decreasing the aromatic content in gasoline fuel may reduce the emissions of total hydrocarbons (THC), nitrogen oxides (NOx), and benzene, but not carbon monoxide (CO), from four-stroke carburetor motorcycles (Yao & Tsai, 2013).

Differences in fuel use and emission rates of carbon dioxide (CO2), carbon monoxide (CO), hydrocarbons (HC), nitrogen oxide (NOx), and particulate matter (PM) were quantified for three gasoline-ethanol blends and neat gasoline measured for one flexible-fuel vehicle (FFV) and four non-FFVs using a portable emission measurement system (PEMS). The purpose was to determine if non-FFVs can adapt to a mid-level blend and to compare the fuel use and emission rates among the fuels. Each vehicle was measured on neat gasoline (E0), 10% ethanol by volume (E10) “regular” (E10R) and “premium” (E10P), and 27% ethanol by volume (E27). Four real-world cycles were repeated for each vehicle with each fuel. Second-by-second fuel use and emission rates were binned into Vehicle Specific Power (VSP) modes. The modes were weighted according to real-world standard driving cycles. All vehicles, including the non-FFVs, were able to adapt to E27. Octane-induced efficiency gain was observed for higher octane fuels (E10P and E27) versus lower octane fuels (E0 and E10R). E27 tends to lower PM emission rates compared to E10R and E10P and CO emission rates compared to the other three fuels. HC emission rates for E27 were comparable to those of E10R and E10P. No significant difference was found in NOx emission rates for E27 versus the other fuels. Inter-vehicle variability in fuel use and emission rates was observed (Yuan et al., 2019).

American Automobile Association conducted primary research in the fuel quality area to better understand the impact and influence of detergent additive packages on engine cleanliness. These additives have been used in commercially available gasoline fuel for more than 20 years to help keep fuel system parts and components clean and prevent the buildup of carbon deposits on critical engine parts and components such as intake valves, fuel injectors, and combustion chamber surfaces. Such deposits disturb airflow and affect air-fuel ratios, which can lead to pre-ignition, detonation, incomplete combustion, reduced fuel economy and increased exhaust emissions (Bardasz et al., 2018).

Gasoline Direct Injection (GDI) has become the preferred technology for spark-ignition engines resulting in greater specific power output and lower fuel consumption, and consequently reduction in CO2 emission. However, GDI engines face a substantial challenge in meeting new and future emission limits, especially the stringent particle number (PN) emissions recently introduced in Europe and China. Studies have shown that the fuel used by a vehicle has a significant impact on engine-out emissions. For study purposes, nine fuels with varying chemical composition and physical properties were tested on a modern turbocharged side-mounted GDI engine with design changes to reduce particulate emissions. The fuels tested...
included four fuels meeting US certification requirements; two fuels meeting European certification requirements; and one fuel meeting China 6 certification requirements. Two risk safeguard fuels (RSG), representing the properties of worst-case market fuels in Europe and China, were also included. The particle number concentration of the solid particulates was measured in the engine-out exhaust flow at steady state engine operations with load and speed sweeps, and semi-transient load steps. The test results showed a factor of 6 PN emission difference among all certification fuels tested. Combined with detailed fuel analyses, the study evaluated important factors (such as oxygenates, carbon chain length and thermo-physical properties) that cause PN emissions which were not included in the PMI index. Linear regression was performed to develop a PN predictive model which showed improved fitting quality than using PMI (Fatouraie et al., 2018).

Particulate Matter (PM) emissions from gasoline direct injection (GDI) engines, particularly Particle Number (PN) emissions, have been studied intensively in both academia and industry because of the adverse effects of ultrafine PM emissions on human health and other environmental concerns. GDI engines are known to emit a higher number of PN emissions (on an engine-out basis) than Port Fuel Injection (PFI) engines, due to the reduced mixture homogeneity in GDI engines. Euro 6 emission standards have been introduced in Europe (and similarly in China) to limit PN emissions from GDI engines. Fuel composition plays an important role in engine-out PM emissions; however, in general, its effects can be masked by other engine operating parameters (for example air-fuel ratio). High levels of aromatic components present in fuel have been conclusively shown to increase PN emissions, an aromatic ring being an early stage of the fundamental particulate formation process. Other fuel composition parameters do have an effect, but are dependent on engine design and operating point. Low levels of oxygenates in fuels show mixed effects but high levels of oxygenating have been shown to reduce PN emissions, with fuels such as E85 capable of giving extremely low levels of particulate emissions (Raza, Chen, Leach, & Ding, 2018).

A study conducted to test on the NEDC gasoline vehicle without special modifications and a flex fuel vehicle (FFV). The fuel blends used were E5 and E10 for the gasoline vehicle and E85 for the flex fuel vehicle (FFV). The results were compared to E0 gasoline fuel. It was found that total carbon dioxide (CO2) emissions reduced by 1.2% for E5 and 4.6% for E85, while they increased by 1.4% for E10. Fuel consumption was found to decrease by 2.5% for E5, while it increased by 4.2% for E10 and by 12.1% for E85 (Delgado & Paz, 2012).

The emissions of E5, E10, E25 and E50 blends measured for NEDC. It was found a small decrease in carbon dioxide (CO2). In the United States, gasoline contains ethanol up to 10% (E10) and since 2011 the use of E15 has been introduced for 2001 and newer vehicles and flex-fuel vehicles (FFVs). The Department of Energy indicates that consumers experience higher fuel consumption due to the lower energy density of ethanol (Bielaczyc, Woodburn, & Szczotka, 2013).

A was comparison made between E0 and E10 carbon dioxide (CO2) emissions for a Dacia Sandero and a Mini Paceman cars, and it was found that with E10 they increased by 11 g/km in the case of the Dacia Sandero and 2 g/km in the case of the Mini Paceman. It was also claimed that the ECU might have misdiagnosed the sensors’ data because of the different fuel composition and injected more fuel (Butcher, 2014).

3. Study objective
The objective of this study is to determine and understand the gasoline fuel quality impact on fuel consumption, air-fuel ratio (AFR), lambda (λ) and exhaust emissions of gasoline-fueled vehicles, which can help in reducing fuel consumption, improving the quality of fuel combustion and reducing vehicle exhaust emissions.

Most of the studies related to gasoline fuel quality are focusing on one or two of the following:
(1) Measuring and studying the impact of gasoline fuel quality on air quality and public health by measuring the impact of gasoline fuel quality on the vehicle exhaust emission gases.

(2) Estimating the financial impact of gasoline fuel quality through measuring the impact of gasoline fuel quality on vehicle fuel consumption.

(3) Studying the gasoline fuel quality on the vehicles engine performance through measuring and studying AFR and $\lambda$ values.

While this study is focusing on and measuring the impact of the gasoline fuel quality on vehicles exhaust emission, fuel consumption and the vehicles engine performance in a way that provide a comprehensive knowledge and information regarding the impact of gasoline fuel quality and helps the decision makers to take the right decisions related to gasoline fuel and its quality.

4. Gasoline fuel quality and octane number

Although particular fuel parameters used may vary based on the jurisdiction and the source of the information, fuel quality specifications address the following characteristics:

- The properties of flow and Combustion
- Impurities concentration
- Impact on the cleanliness and wear of the engine and related parts and components

The Worldwide Fuel Charter (WWFC) provides common rules for assessing fuel characteristics and standards internationally. The WWFC has been developed by major vehicle manufacturers from around the world. The WWFC is intended to provide globally relevant recommendations on quality of fuel to help reduce the environmental impact of vehicles, increase customer satisfaction and reduce customer costs by minimizing the complexity of vehicle equipment and related maintenance issues. Members of the committee publishing the WWFC include the European Automobile Manufacturers Association, the Engine Manufacturers Association, the Alliance of Automobile Manufacturers, and the Japan Automobile Manufacturers Association (JAMA). The Canadian Vehicle Manufacturers’ Association and the Association of International Automobile Manufacturers of Canada are both associate members in the partnership that publishes the WWFC. The Worldwide Fuel Charter (WWFC) is periodically updated, acting as a living document which is intended to reflect developments in engine, changes in market conditions and emissions control technologies and as a result, changes in the quality requirements of fuel (Row & Doukas, 2008).

Gasoline octane number is a gasoline’s ability to measure to resist auto ignition, which can cause engine knock and severely damage engines. Two laboratory test methods are used to measure octane: one determines the Research Octane Number (RON) and the other determines the Motor Octane Number (MON). The Research Octane Number (RON) correlates best with low speed, mild knocking conditions, and the Motor Octane Number (MON) correlates with high temperature knocking conditions and with part throttle operation. The Research Octane Number (RON) values are typically higher than the Motor Octane Number (MON), and the difference between these values is the sensitivity, which should not exceed 10. In North America, $(\text{RON} + \text{MON})/2$ is typically used to specify the gasoline octane rating, while many other markets typically specify the Research Octane Number (RON) (ACEA-Alliance-EMA—JAMA, 2013).

The gasoline octane rating is a measure of a fuel’s ability to avoid knock. Knock occurs when fuel is prematurely ignited in the engine’s cylinder, which reduces efficiency and can damage the engine. Knock is practically unknown to modern drivers. This is primarily because fuels contain an oxygenate that prevents knock by adding oxygen to the gasoline fuel. This oxygenate is commonly referred to as octane (Stolark, 2016).

At most retail gasoline fuel stations, three octane grades gasoline fuel is offered, 87 (regular), 89 (mid-grade), and 91–93 (premium). The higher the octane number, the more resistant the gasoline...
fuel mixture is to knock. The use of higher octane fuels also enables higher compression ratios, turbo-charging, and downsizing/down-speeding all of which enable higher performance and greater engine efficiencies. Currently, high octane gasoline fuel is marketed as premium, but vehicle manufacturers have expressed interest in raising the minimum octane number in the United States to enable smaller, more efficient engines. Doing so would increase vehicle efficiency and lower greenhouse gases (GHGs) through decreased fuel consumption (Auto News, 2015).

5. Fuel consumption
Fuel consumption is adverse to fuel efficiency. Hence, it may be defined as the amount of fuel consumed per unit distance, expressed in liters/100 km. Lower is the value of fuel consumption, more economical is the vehicle. That is less amount of fuel will be consumed to travel a certain distance (Mathew, 2014).

6. Air-fuel ratio (AFR) and lambda ($\lambda$)
The AFR is an important measure for performance tuning and anti-pollution reasons. If exactly enough air is provided to completely burn all of the fuel, the ratio is known as the stoichiometric mixture. Air-fuel (AFR) numbers lower than stoichiometric are considered rich mixture, which is less efficient, but may produce more power and burns cooler, which is kinder on the engine. AFR numbers higher than stoichiometric are considered lean mixture, which is more efficient but may cause engine damage or premature wear and produce higher levels of nitrogen oxides. Unfortunately, a stoichiometric mixture burns very hot and can damage the components of the engine if the engine is placed under high load at a stoichiometric mixture. Because of the high temperatures at this mixture, the detonation of the fuel-air mix shortly after maximum cylinder pressure is possible under high load (knocking or pinging). Detonation can cause serious engine damage as the uncontrolled burning of the fuel-air mix can create very high pressures in the cylinder. As a result, stoichiometric mixtures are only used under the conditions of light loads. For high load conditions and acceleration, a richer mixture is used to produce cooler combustion products and that way prevent detonation and overheating of the cylinder head. The AFR is the most common reference term used for mixtures in internal combustion engines, and it is computed with Equation 1 (World Heritage Encyclopedia, 2016).

$$AFR = \frac{m_{air}}{m_{fuel}}$$  \hspace{1cm} (1)

Where

- $m_{air}$ = mass of air,
- $m_{fuel}$ = mass of fuel

Air-fuel equivalence ratio, lambda ($\lambda$), is the ratio of actual AFR to stoichiometric AFR. For a given mixture, $\lambda = 1.0$ is at stoichiometric AFR, rich mixtures have $\lambda < 1.0$, and lean mixtures have $\lambda > 1.0$. There is a direct relationship between $\lambda$ and AFR. To calculate AFR from a given $\lambda$, multiply the measured $\lambda$ by the stoichiometric AFR for that fuel. Alternatively, to recover $\lambda$ from an AFR, divide AFR by the stoichiometric AFR for that fuel. Equation 2 is often used as the definition of $\lambda$ (Aditya & Anil, 2016):

$$\lambda = \frac{AFR}{AFR_{stoich}}$$  \hspace{1cm} (2)

Where

- $AFR$ = actual AFR
- $AFR_{stoich}$ = stoichiometric AFR
Because the composition of common fuels varies seasonally, and because many modern vehicles can handle different fuels when tuning, it makes more sense to talk about lambda (\(\lambda\)) values rather than air-fuel ratio (AFR). Most practical measurement air-fuel ratio (AFR) devices actually measure the amount of residual oxygen (for lean mixes) or un-burnt hydrocarbons (for rich mixtures) in the vehicles exhaust emissions (World Heritage Encyclopedia, 2016).

7. The gasoline-fueled vehicle exhaust emissions

The amount of carbon dioxide (CO2) created from burning one gallon of fuel depends on the amount of carbon in the fuel. Typically, more than 99% of the carbon in fuel is emitted as carbon dioxide (CO2) when the fuel is burned. Very small amounts are emitted as hydrocarbons (HC) and carbon monoxide (CO), which are converted to carbon dioxide (CO2) relatively quickly in the atmosphere. Carbon content varies by fuel, and some variation within each type of fuel is normal (Environmental Protection Agency (EPA), 2014).

In addition to carbon dioxide (CO2), vehicles produce carbon monoxide (CO), sulfur Oxides (Sox), nitrogen oxides (NOx), and particulate matter (PM). The pollutants which are emitted from the vehicle exhaust pipe are known as exhaust pollutants. They are formed as a result of fuel combustion in the engine. These pollutants are harmful to the atmosphere and living things in particular. The major types of exhaust pollutants are summarized in the following (Mathew, 2014):

- **Carbon Dioxide (CO2):** It is an indicator of complete combustion of the fuel. Although it does not directly affect the public health, it is a greenhouse gas (GHG) which causes global warming.
- **Hydrocarbons and Volatile Organic Compounds (HC and VOCs):** Hydrocarbons result from the incomplete combustion of fuels. Their subsequent reaction with the sunlight causes smog and ground level Ozone formation. Volatile Organic Compounds (VOCs) are a special group of Hydrocarbons. They are divided into two types, methane, and nonmethane.
- **Carbon Monoxide (CO):** It is a product of the incomplete burning of fuel and is formed when Carbon is partially oxidized. Carbon Monoxide (CO) is a colorless gas, odorless, but is toxic in nature. It reaches the bloodstream to form Carboxyhemoglobin, which reduces the flow of Oxygen in blood.
- **Nitrogen Oxides (NOx):** Combustion under high pressure and temperature emits nitrogen dioxide. It is a reddish brown gas. Nitrogen oxides (NOx) contribute to the formation of acid rain and ground level Ozone.
- **Sulfur Oxides (SOx):** Combustion of gasoline generates sulfur dioxide (SO2). It is a pungent, colorless and non-flammable gas. It causes respiratory illness but occurs only in very low concentrations in exhaust emission gases. Further oxidation of Sulfur Oxides (SOx) forms H2SO4 and thus acid rains.
- **Lead (Pb):** It is a malleable heavy metal. Lead (Pb) present in the gasoline fuel to help in preventing engine knocks. Lead (Pb) causes harm to the reproductive and nervous systems. It is a neurotoxin which accumulates in the bones and soft tissues.
- **Particulate Matter (PM):** These are tiny liquid or solid particles suspended in the gas. Particulate matter (PM) in higher concentrations may lead to lung cancer and heart diseases.

8. Study vehicle

For the purposes of this study, Nissan Tiida car was selected, the car manufacturing year is 2009 and it is a gasoline-fueled vehicle (fuel free of lead) with 1.6-liter engine capacity (see Figure 3). The car design average fuel consumption is 8.5 liter/100 Km.

9. The study air-fuel ratio (AFR), lambda (\(\lambda\)) and exhaust emissions measurement tool (exhaust gas analyzer)

For the purposes of the air-fuel ratio (AFR), lambda (\(\lambda\)) and exhaust emissions measurement of this study, the E instruments model F5000-5GAS was selected (see Figure 4). The F5000-5GAS is an
extremely versatile and portable emissions measurement system designed to measure and analyze exhaust gases from vehicles, trucks, buses, and forklifts. It has been designed as a modular system, permitting the installation, in the field, of most of the various available options. The E INSTRUMENTS Model F5000-5GAS is a portable state-of-the-art exhaust gas analyzer designed to measure, record, and remotely transmit combustion parameters used for the following tasks (E Instruments International LLC, 2017):

1. To accurately measure air-fuel ratio (AFR), lambda (\( \lambda \)), O2, CO2, CO, HC, and NO/NOx from the engine exhaust pipes of automobiles, forklifts, trucks, buses, and other vehicles running on fuels such as gasoline, diesel, LPG, CNG, and propane.

2. To perform routine engine tuning and maintenance, and to help diagnose potential engine problems.
(3) To assist in servicing a vehicle to the manufacturer’s emissions specifications, and for pre-compliance verification testing.

(4) To assist the operator of a vehicle with the task of optimizing its engine efficiency, performance, and fuel savings.

(5) To be used as a management tool to assist the operator with keeping records and controlling costs.

The E INSTRUMENTS F5000-5GAS uses sophisticated electronics and programming design for increased accuracy and flexibility. It measures five different exhaust gases and calculates the air-fuel ratio (AFR) and Lambda (λ). It stores, prints and graphs data. It communicates with a variety of other computers, tablets, and other Windows compatible devices located nearby using Bluetooth wireless technology and/or USB cable. It has a library of six fuels, and the operator can add more fuels if needed. It is designed to operate on its internal rechargeable battery pack as well as AC power (E Instruments International LLC, 2017). The technical specification of The E INSTRUMENTS Model F5000-5GAS analyzer is summarized in Table 1.

10. Results and discussion
The study vehicle, along with the study duration filled with gasoline from five different fuel stations in order to get gasoline with different quality. A sample of gasoline was collected with every fuel refill for the purpose of the gasoline fuel quality test. The quality test for the five gasoline samples is conducted by Garmian Directorate of Petrol and Minerals Quality Control-Parwizkhan Fuel Test Unit; the test results of the gasoline fuel samples are summarized in Table 2.

For every gasoline fuel refill, the fuel consumption calculated and vehicle exhaust emissions measurement conducted (see Figures 5 and 6 and Table 3).

The study results indicated an impact of the gasoline fuel quality on fuel consumption, air-fuel ratio (AFR), lambda (λ) and exhaust emissions. The study results were discussed in the following:

10.1. The impact of gasoline fuel quality on fuel consumption
The results indicated that as the gasoline octane number increases the fuel consumption increase (see Tables 2 and 3 and Figure 7). Higher octane gasoline has lower energy content per liter compared to regular gasoline; a vehicle’s volumetric fuel consumption generally increases as the used gasoline fuel is with higher octane number, which means the vehicles consume more gasoline fuel with higher quality than the normal or low-quality gasoline for the same distances.

10.2. The impact of gasoline fuel quality on air-fuel ratio (AFR) and lambda (λ)
The results indicated that in general as the benzene and aromatic content increase in the gasoline, the air-fuel ratio (AFR) and lambda (λ) values decrease (see Tables 2 and 3 and Figures 8–11). As

| Parameter | Sensor | Range | Resolution | Accuracy |
|-----------|--------|-------|------------|----------|
| CO₂       | NDIR   | 0–20% | 0.1 %      | 0.1% ±3% rdg. |
| CO        | NDIR   | 0–15% | 0.01 %     | 0.02% ±3% rdg. |
| HC        | NDIR   | 0–10,000 ppm | 1 ppm | ±3% rdg. (301–4,000 ppm) ±8 ppm (0–300 ppm) ±5% rdg. (4,001–10,000 ppm) |
| O₂        | Electrochemical | 0–25% | 0.1% | ±0.1% vol |
| NO/NOx    | Electrochemical | 0–5,000 ppm | 1 ppm | <125 ppm = ±5 ppm up to 5,000 ppm = ±4% |
| Analysis                  | Unit               | Gasoline Quality Specifications (Iraqi specifications) | Sample no.1 | Sample no.2 | Sample no.3 | Sample no.4 | Sample no.5 |
|--------------------------|--------------------|--------------------------------------------------------|-------------|-------------|-------------|-------------|-------------|
|                          |                    | Normal (Limits) | Enhanced (Limits) | Super (Limits) | Normal  | Normal  | Normal  | Normal  | Enhanced |
| Octane no.               | Mon + Ron/2        | 88             | 90                | 92             | 85      | 92      | 86      | 92.5    | 86       | 93       | 88       | 95       |
| Density at 15 °C         | gm/m³              | 0.72-0.75      | 0.72-0.75         | 0.72-0.75      | 0.73    | 0.72    | 0.72    | 0.73    | 0.73     | 0.73     | 0.73     | 0.73     |
| Benzene content (max)    | % V                | 1              | 1                 | 1              | 0.47    | 0.4     | 0.4     | 0.56    | 0.56     | 0.6      | 0.8      |
| Aromatic Content (max)   | % V                | 35             | 35                | 35             | 19      | 18      | 17      | 21      | 21       | 24       | 24       |
| Olefins content (max)    | % V                | 18             | 18                | 18             | 5       | 4       | 2       | 5.8     | 5.8      | 4        | 4        |
| Initial boiling point    | ° C                | Without range  | 38                | 35             | 37      | 37      | 39      |         |          |          |          |
| Final boiling point (max)| ° C                | 210            | 210               | 210            | 191     | 187     | 185     | 184     | 189      |          |          |
| Oxygen content (max)     | % wt               | 2.7            | 2.7               | 2.7            | 0.36    | 1.2     | 1.2     | 1.56    | 1.2      |          |          |
| Toluene (max)            | % V                | 10             | 10                | 10             | 5       | 5       | 5       | 7       | 7        | 7        | 7.2      |
| TAME (max)               | % V                | 10             | 10                | 10             | 6       | 2       | 2       | 2       | 6        |          |          |
the air-fuel ratio (AFR) and lambda (λ) values decrease toward the stoichiometric mixture (AFR = 14.7 and λ = 1), the combustion of gasoline fuel become better and closer to the ideal combustion, which mean increasing the benzene and aromatic content in the gasoline fuel is increasing the vehicles engines efficiency by improving the combustion process of the gasoline fuel in the engine.

10.3. The impact of gasoline fuel quality on vehicle exhaust emissions

The impact of gasoline quality on the exhaust emissions is discussed as in the following:

(A) The impact of gasoline fuel quality on carbon dioxide (CO2) exhaust emission: the results indicated that as the gasoline benzene and aromatic content increase, the carbon dioxide (CO2) exhaust emission increase (see Tables 2 and 3 and Figures 12 and 13). Increasing gasoline benzene and aromatic content improve the gasoline fuel combustion toward the ideal combustion. In the ideal or complete combustion of gasoline fuel produce only carbon dioxide (CO2) and water. Then, as a result increasing benzene and aromatic content improves the gasoline quality in term of combustion in the vehicles engines which lead to increase the carbon dioxide (CO2) exhaust emission.

(B) The impact of gasoline fuel quality on oxygen (O2) exhaust emission: the results indicated that as the gasoline benzene and aromatic content increase, the oxygen (O2) exhaust emission decreases (see Tables 2 and 3 and Figures 12 and 13). Increasing gasoline benzene and aromatic content improve the gasoline fuel combustion toward the ideal combustion, wherein the ideal combustion, all the oxygen will be consumed. Then, as a result increasing benzene and aromatic content improves the gasoline quality in term of combustion in the vehicles engines which lead to decrease the oxygen (O2) exhaust emission.

(C) The impact of gasoline fuel quality on carbon monoxide (CO) exhaust emission: all the five carbon monoxide (CO) exhaust emission measurements were zero percentage; therefore, in this study, no indicator can be considered regarding the impact of gasoline fuel quality on carbon monoxide (CO) exhaust emission (see Table 3).

(D) The impact of gasoline fuel quality on nitrogen oxides (NOx) exhaust emission: The results indicated that as the gasoline octane number increases, the nitrogen oxides (NOx) exhaust emission decreases except for the fifth gasoline fuel refill (see Tables 2 and 3 and Figure 14). Gasoline fuel with higher octane number burns cooler, which mean less oxidation of nitrogen
already exists in the air mixed with the gasoline fuel in the combustion chamber and produces lower levels of nitrogen oxides (NOx) exhaust emission. Therefore, combustion of a higher quality of gasoline fuel in term of octane number produces fewer nitrogen oxides (NOx) exhaust emission.

(E) The impact of gasoline fuel quality on hydrocarbons (CxHy) exhaust emission: the study results indicated that the gasoline benzene and aromatic content have an indirect effect on hydrocarbons (CxHy) exhaust emission. As the benzene and aromatic content increase in the gasoline, the air-fuel ratio (AFR) and lambda (λ) values decrease, and as the air-fuel ratio (AFR) and lambda (λ) values decrease toward the stoichiometric mixture (AFR = 14.7 and λ = 1), the combustion of gasoline fuel become better and closer to the ideal combustion. The hydrocarbons (CxHy) exhaust emission is uncombusted fuel produced from incomplete combustion of fuel. As the combustion
Table 3. Fuel consumption, air-fuel ratio (AFR), lambda (λ) and exhaust emissions for every gasoline fuel refill

| No. | Fuel Consumption (liter/100 Km) | Vehicle Exhaust Emissions |  |
|-----|---------------------------------|---------------------------|---|
|     |                                 | O2 (%) | CO2 (%) | CO (%) | CxHy (ppm) | NO (ppm) | Air-Fuel Ratio (AFR) | Lambda (λ) |
| 1-  | 8.395                           | 1.3    | 14.4    | 0.00   | 0          | 51       | 15.59                | 1.06       |
| 2-  | 8.563                           | 2.1    | 13.8    | 0.00   | 75         | 46       | 16.18                | 1.10       |
| 3-  | 8.980                           | 4.4    | 11.5    | 0.00   | 71         | 35       | 18.38                | 1.25       |
| 4-  | 9.167                           | 3.8    | 12.5    | 0.00   | 85         | 17       | 17.50                | 1.19       |
| 5-  | 9.013                           | 1.6    | 13.7    | 0.00   | 47         | 44       | 15.73                | 1.07       |
Figure 7. The relationship between gasoline octane number and fuel consumption.

Figure 8. The relationship between gasoline benzene content and air-fuel ratio (AFR).

Figure 9. The relationship between gasoline benzene content and lambda (\(\lambda\)).

Figure 10. The relationship between gasoline aromatic content and air-fuel ratio (AFR).
Figure 11. The relationship between gasoline aromatic content and lambda (\(\lambda\)).

Figure 12. The relationship between gasoline benzene content and carbon dioxide (CO2) and oxygen (O2) exhaust emission percentages.

Figure 13. The relationship between gasoline aromatic content and carbon dioxide (CO2) and oxygen (O2) exhaust emission percentages.

Figure 14. The relationship between gasoline octane number and nitrogen oxides (NOx) exhaust emission concentration.
gets better, the values of the hydrocarbons (CxHy) exhaust emission get smaller toward zero in the ideal combustion (see Table 3).

11. Conclusion
Based on the results of this study, the following can be concluded:

(1) The gasoline fuel consumption increase with the increase of its octane number because higher octane gasoline has lower energy content per liter compared to regular gasoline, a vehicle’s volumetric fuel consumption generally increases as the used gasoline fuel is with higher octane number.

(2) When the benzene and aromatic content increase in the gasoline, the air-fuel ratio (AFR) and lambda (λ) values decrease. Whenever the air-fuel ratio (AFR) and lambda (λ) values decrease toward the stoichiometric mixture (AFR = 14.7 and λ = 1), the combustion of gasoline fuel become better and closer to the ideal combustion.

(3) Increasing gasoline benzene and aromatic content will increase the carbon dioxide (CO2) exhaust emission, where increasing gasoline benzene and aromatic content improve the gasoline fuel combustion toward the ideal combustion. In the ideal or complete combustion of gasoline fuel produce only carbon dioxide (CO2) and water.

(4) When the gasoline benzene and aromatic content increase, the oxygen (O2) exhaust emission will decrease. Increasing gasoline benzene and aromatic content improve the gasoline fuel combustion toward the ideal combustion, wherein the ideal combustion, all the oxygen will be consumed.

(5) As the gasoline octane number increases, the nitrogen oxides (NOx) exhaust emission decreases. Gasoline fuel with higher octane number burns cooler, which mean less oxidation of nitrogen already exists in the air mixed with the gasoline fuel in the combustion chamber and produces lower levels of nitrogen oxides (NOx) exhaust emission.

(6) The gasoline benzene and aromatic content have an indirect effect on hydrocarbons (CxHy) exhaust emission. When the benzene and aromatic content increase in the gasoline, the air-fuel ratio (AFR) and lambda (λ) values decrease and whenever the air-fuel ratio (AFR) and lambda (λ) values decrease toward the stoichiometric mixture (AFR = 14.7 and λ), the combustion of gasoline fuel become better and closer to the ideal combustion. The hydrocarbons (CxHy) exhaust emission is uncombusted fuel produced from incomplete combustion of fuel, as the combustion gets better the values of the hydrocarbons (CxHy) exhaust emission get smaller toward zero in the ideal combustion.

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