



# Experimental investigation of the effects of coolant temperature in a turbocharged stratified injection (TSI) engine fuelled with gasoline and liquefied petroleum gas

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## ARTICLE INFO

### Keywords:

TSI engine  
Coolant temperature  
Gasoline direct injection  
LPG indirect injection  
LPG direct injection

## ABSTRACT

This study investigates the effects of using the TSI engine with alternative fuels, which many commercial vehicle brands have started to prefer in their vehicles. This study investigated turbocharged stratified injection engine (TSI) emissions using different coolant temperatures (20 °C, 40 °C and 90 °C) under steady-state operating conditions. Three different fuel strategies were used: gasoline, gasoline with liquefied petroleum gas (LPG), and liquid LPG. Furthermore, three different operating conditions as motoring, 2500 RPM-105 km/h and 3500 RPM-145 km/h were applied in experimental studies. The results indicated that cooling temperature has a strong effect on emissions that in cold working conditions due to incomplete combustion, NO<sub>x</sub> emissions were decreased while CO and HC emissions were increased. From the results, emissions of liquid DI-TSI LPG fuel were more sensitive than other fuels to coolant temperature, and increasing the temperature decreases the HC and CO emissions more than other fuels.

## 1. Introduction

Because internal combustion engines are still the most important equipment in transportation, much research continues to improve combustion efficiency and reduce exhaust emissions [1–3]. Due to the soot and NO<sub>x</sub> emission problems in diesel engines, other concepts such as gasoline engines, hybrids engine, and electric motors are becoming preferable to diesel engines in passenger cars. New developments in spark ignition (SI) engines allow the use of different fuels. Thanks to these new fuels, emissions such as hydrocarbons (HC) and nitrogen oxides (NO<sub>x</sub>) can be reduced [4–7]; also, power and efficiency can increase, and production costs can decrease. One of the important improvements for SI engines was the direct injection (DI) strategy which provides higher combustion efficiency, controlling the combustion by reducing HC and CO emissions compared to the port fuel injection (PFI) strategy [8,9]. One recently developed SI engine concept is a turbocharged stratified injection engine (TSI). Direct Injection Turbocharged Spark Ignition engines (DI-TSI) come to the fore, especially to reduce hydrocarbon (HC) emissions in spark ignition (SI) engines. Combining a turbocharger with direct injection gives a significant advantage in this

concept. It reduces the engine downsizing by reducing toxic emissions, pumping losses, and in-cylinder gas temperatures while improving combustion efficiency and fuel economy compared to conventional PFI and DI spark ignition engines [6–8]. Also, DI-TSI engines are famous for their high power and torque. Reducing emissions of traditional fossil fuels has become a target agreed upon by all countries worldwide. Internal combustion engines continue to maintain their importance in vehicles used in transportation, so a large amount of fossil fuel consumption and serious emissions occur. Today, restrictions are applied in many countries to reduce emissions. Some motor manufacturers, foreseeing that they will not be able to overcome the new limitations, have announced to stop the production of diesel engines for passenger vehicles soon due to emission problems [9]. Therefore, gasoline and alternative fuels will be expected to increase. One of the most popular environmentally friendly and economical alternative fuels, liquefied petroleum gas (LPG) is a gas mixture consisting of hydrocarbon gases, mainly propane (C<sub>3</sub>H<sub>8</sub>) and butane (C<sub>4</sub>H<sub>10</sub>) and other gases such as propane (C<sub>3</sub>H<sub>6</sub>), n-butane (C<sub>4</sub>H<sub>10</sub>), iso-butane (methyl-propane) [10]. The most important features of these fuels are that they can be used on internal combustion engines without changing the engine. In addition,

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<https://doi.org/10.1016/j.fuel.2023.127988>

Received 27 December 2022; Received in revised form 16 February 2023; Accepted 24 February 2023

Available online 2 March 2023

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LPG has similar physical properties to gasoline, which is an important factor in its preference. LPG fuel can be used easily in spark ignition engines because of its properties close to gasoline fuel. With the widespread use of LPG fuel in vehicles, some companies in some countries have started producing LPG-fueled cars from the factory [11]. In addition to the economic dimension of LPG, it can be an alternative fuel to gasoline due to its high octane number, high thermal efficiency, production, and supply from many sources [12]. LPG fuel can vaporize and mix faster with the inlet air, helps increase its thermal efficiency and decrease particulate emission [13].

As a result of the studies carried out over the years, it has been ensured that the emissions of DI spark-ignition engines are continuously reduced. However, there are still some problems to be solved and among these problems, improving cold working conditions in terms of emissions is an important issue. DI spark-ignition engines emit more particulate matter during cold start than PFI engines. In the cold working condition of an SI engine, direct-injected low-temperature fuel accumulates on the liner surface because of the cold cylinder liner walls [13–15]. These local fuel-rich mixtures cause high PM emissions because of incomplete combustion [17]. Using alternative fuels on DI spark-ignition engines at cold working conditions affects the combustion and emissions in different ways. For example, the high latent heat value of the ethanol additive in gasoline fuel delays the vaporization increases wall wetting at lower cooling temperatures and increases emissions [16–21]. Direct-injected liquid LPG fuel has a potential cooling effect on the in-cylinder mixture like ethanol fuel because of its high latent heat. Therefore, it is expected to increase hydrocarbon (HC) and CO emissions in cold working conditions. In this study, a comparative investigation was done between gasoline, gasoline + PFI LPG, and liquid DI-TSI LPG fuels effects in cold working conditions on a TSI engine. The TSI engine vehicle's CO<sub>2</sub>, CO, HC, and NO<sub>x</sub> emissions were obtained under different coolant water temperatures and vehicle speeds.

## 2. Materials and methods

The experiments in this study were carried out on a vehicle. For this purpose, the vehicle was placed on a vehicle dynamometer, and the environment in real road conditions was tried to be provided. In all vehicle tests, the conditions required to be performed on the chassis dynamometer in the vehicle emission test protocol of the EU regulation have been met [22]. The diagram of the experimental setup is given in Fig. 1.

The characteristics of the test vehicle are given in Table 1. The room where the vehicle tests are carried out should be air-conditioned and ventilated. During all the experiments, real on-road conditions were provided with a fan that can create an airflow of 7000 m<sup>3</sup>/h at 45 km/h to include an air-cooling effect on the stationary engine. During the

**Table 1**

Technical specifications of an experimental vehicle.

Description	Specification
Engine Type	4-stroke turbocharged gasoline direct injection
Engine Volume (cm <sup>3</sup> )	1591
Vehicle Maximum Speed (km/h)	201
Maximum Power (kW)	132/5500 min <sup>-1</sup>
Maximum Torque (Nm)	265/4500 min <sup>-1</sup>
Injection Type	Direct
Number of Cylinders	4
Number of Valves	16 valve
Engine Compression Ratio	10:1
Cooling system	Water cooling
Transmissions Type	7 DCT
Tire Size	245/45 R19
Vehicle Weight	1495 kg

experiments, the indoor air temperature of 20 °C and humidity of 40% was kept constant with the air condition system. The technical characteristics of the Dyno Race 2WD brand chassis dynamometer used in the experimental study are given in Table 2.

Vehicle experiments were repeated at the engine's idle speed, at 2500 rpm/105 km/h and 3500 rpm/145 km/h. Experiments were carried out in the 5th gear state, where the gear position of the vehicle was 1:1. By taking the data of the engine computer via the Bosch brand fault diagnosis device, the engine's coolant temperature was instantly read and controlled. In addition, the data received via the computer were checked by comparing them with thermocouples integrated into the engine coolant system and laser temperature measuring devices. The experiments started before 3 °C for each temperature value and were terminated when 3 °C passed [22]. In addition, it was expected that the engine body temperature would drop by 10 °C by introducing the vehicle to the external environment. For each measurement, the cooling water of the vehicle was drained from the system and experiments were started by adding cooling water at a temperature of 10 °C. Thus, it was ensured that experiments were carried out with engine cooling water at the same temperature at each stage.

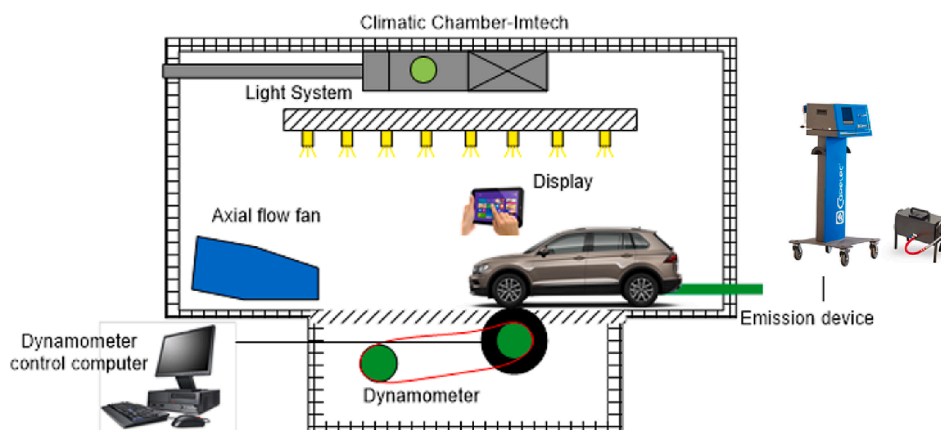
It is known that the engine load is changed by increasing or

**Table 2**

Technical specifications of a chassis dynamometer (Dyno Race 2WD).

Dynamometer specifications	Value
Maximum Power (HP)	535 HP
Maximum Torque (Nm)	1500 Nm
Traction System	2WD
Maximum Speed	300 km/h

\*DIN70020, EGW 80/1269, ISO 1585, SAEJ1349, JIS D1001.



**Fig. 1.** Experimental test schematic diagram.

decreasing the vehicle speed in the studies carried out in the chassis dynamometer. In this study, it was decided to carry out the experiments at the two vehicle speeds determined. The determined speeds are set via the vehicle's speed control system. The speed value is read on the control system and the vehicle indicator and adjusted precisely at the desired speed value. For this reason, the vehicle speed could be kept constant under each experimental condition. In addition, it was observed that the vehicle was at vehicle speeds of 105 km/h and 145 km/h, 2500 rpm, and 3500 rpm through the vehicle's cruise control system under each fuel mixture value and operating conditions. Thus, the engine was loaded under the same conditions every time. The weights of the LPG kits added to the vehicles and the technician who performed the vehicle test were ignored because they were fixed every time. With the diagnostic tester of the LPG kit manufacturer, the fuel consumption values for gasoline, gasoline + PFI LPG, and liquid DI-TSI LPG were recorded under all experimental conditions. The obtained data were calculated, and the Brake Specific Fuel Consumption (BSFC) value was calculated [23,24]. The formulations specified in the equations (1, 2, 3) were used to calculate fuel consumption values.

$$\text{Fuel Consumption} \left[ \frac{l}{100 \text{ km}} \right] = \frac{\text{Fuel Flow} \left( \frac{l}{h} \right)}{\text{Vehicle Speed} \left( \frac{km}{h} \right)} \times 100 \quad (1)$$

$$\text{Fuel Consumption} \left[ \frac{g}{h} \right] = \text{Fuel Flow} \left( \frac{l}{h} \right) \times \rho \left( \frac{g}{l} \right) \quad (2)$$

$$\text{BSFC} \left[ \frac{g}{kWh} \right] = \frac{\text{Fuel Consumption} \left( \frac{g}{h} \right) \times 1000}{P \text{ (kW)}} \quad (3)$$

$$\rho = \text{Density} \left( \frac{g}{l} \right)$$

The two different fuels used in the experiments are gasoline and LPG. Table 3 shows the chemical properties of the test fuels. Gasoline and LPG were purchased from a commercial company that sells locally.

### 2.1. Fuel systems of the experimental vehicles

Gasoline and gas-phase LPG fuels can operate in the same vehicle using separate injection systems. However, the liquid DI-TSI LPG system needs different injection and control apparatus, it was not possible to use it together with the gas phase LPG system. Therefore, the same brand and model two vehicles have a gas phase LPG system and a liquid DI-TSI LPG system used for experiments. Prins VSI 2.0 [25] system for gas phase LPG and Prins Direct LiquiMax [26] for liquid LPG were used for the experimental setup. The equipment that makes up the LPG systems weighs 50 kg. Experiments with gasoline fuel did by disabling the LPG injection. In the port injection LPG system, 1% gasoline was injected at 2500 rpm, while gasoline injection was increased to 5% at 3500 rpm vehicle speed. Fuel injects directly into the cylinder with an apparatus attached to the vehicle's existing injector in liquid DI-TSI LPG systems. Thus, a direct injection liquid DI-TSI LPG system aims for better combustion performance, exhaust emission, and fuel consumption. Gasoline fuel was injected into the cylinder at 200 bar while liquid DI-TSI LPG 2000 bar and gas phase LPG 2.2 bar. Schematics of gas-phase LPG and liquid DI-TSI LPG systems used in experimental vehicles are given respectively in Fig. 2 and Fig. 3.

Experiments were carried out separately on two vehicles with liquid-

**Table 3**  
Technical properties of the test fuels.

	Unleaded Gasoline	Propane	Butane
Density (kg/m <sup>3</sup> )	756	509	585
Lower Calorific Value (MJ/kg)	44.04	46.34	45.56
Boiling Temperature (°C)	30–225	–42	–0.5
Ignition Temperature (°C)	257	510	490
Research Octane Number	95	111	103

phase LPG and gas-phase LPG systems, which are the most widely used Prins brand LPG system for the same vehicle. Thus, the different LPG systems of the two vehicles were compared under cold start conditions.

Exhaust emission measurements were made with Capalec CAP 3201-4 Gas device. Measurements of HC, CO, CO<sub>2</sub>, and NO<sub>x</sub> gases were made according to engine coolant temperature and different vehicle speeds. The uncertainty analysis values of measured gases are given in Table 4.

### 3. Experimental results

Gasoline, liquid, and gaseous LPG fuels were tested in two TSI engine vehicles with a chassis dynamometer at cold start working conditions. Experiments were repeated for three different engine coolant temperatures and vehicle speed conditions. The effects of different fuels, injection systems, coolant temperatures and vehicle speed on emissions were investigated. CO<sub>2</sub>, HC, CO, BSFC and NO<sub>x</sub> measurements were compared.

BSFC values at different vehicle speeds and coolant temperatures are given in Fig. 4. BSFC refers to the fuel used for one kW of work per hour. BSFC decreased for all fuel mixtures and vehicle speeds when increasing the coolant temperature. The decrease is thought to be caused by the effect of the end-of-combustion temperature formed by the increasing fuel amount and the residual gases remaining in the cylinder. As the engine warms up, most of the air/fuel mixture entering the cylinder burns, and the combustion efficiency increases. It has been determined that the vehicle with the liquid DI-TSI LPG system provides a lower fuel consumption performance than the gasoline + PFI LPG. The findings show that the lowest fuel consumption (206 g/kWh) was obtained from the liquid DI-TSI LPG system at 90 °C engine coolant temperature and 2500 rpm-105 km/h engine conditions. It is thought that LPG's calorific value and high octane number provide an advantage in fuel consumption.

CO<sub>2</sub> emission values at different vehicle speeds and coolant temperature conditions are given in Fig. 5. The highest CO<sub>2</sub> emission was obtained from the gasoline + PFI LPG system at idle speed at 90 °C working conditions. The lowest CO<sub>2</sub> was obtained in 2500 rpm-105 km/h and 20 °C working conditions for the gasoline fuel. Considering that CO<sub>2</sub> formation is an indicator of complete combustion, it can be said that the liquid DI-TSI LPG system provides more ideal conditions at other vehicle speeds, except for the idle speed. In addition, CO<sub>2</sub> emissions increased with the increase in engine coolant temperature. It can be said that higher combustion efficiency cannot be achieved under engine-cold operating conditions.

NO<sub>x</sub> emission values at different vehicle speeds and coolant temperature conditions are given in Fig. 6. The highest NO<sub>x</sub> emission occurred with the liquid DI-TSI LPG system at 3500 RPM-145 km/h vehicle speed. Also, the lowest NO<sub>x</sub> emission occurred at idle speed. In addition, NO<sub>x</sub> emissions increased with the increase in engine coolant temperature and vehicle speed. It is known that NO<sub>x</sub> formation begins when the combustion temperature rises above 1600 K. Especially when engine coolant temperature and vehicle speed are low, NO<sub>x</sub> emission is minimum. The highest NO<sub>x</sub> formation occurred at all vehicle speeds and engine coolant temperatures in the liquid DI-TSI LPG system. The reason for this can be said that the combustion temperature in the liquid DI-TSI LPG systems is higher than in gasoline and gasoline + PFI LPG systems.

CO emission values at different vehicle speeds and coolant temperature conditions are given in Fig. 7. The highest CO emission occurred with the liquid DI-TSI LPG system at idle speed. Also, the lowest CO<sub>2</sub> emission occurred at 3500 RPM-145 km/h. Considering that CO formation is an indicator of incomplete combustion, it can be said that the liquid DI-TSI LPG system provides more ideal conditions at 90 °C engine coolant temperature. In addition, CO emissions decreased with the increase in engine coolant temperature in the liquid DI-TSI LPG systems. In gasoline and gasoline + PFI LPG systems, the lowest CO emission occurred at 2500 RPM-105 km/h vehicle speed.

HC emission values at different vehicle speeds and coolant

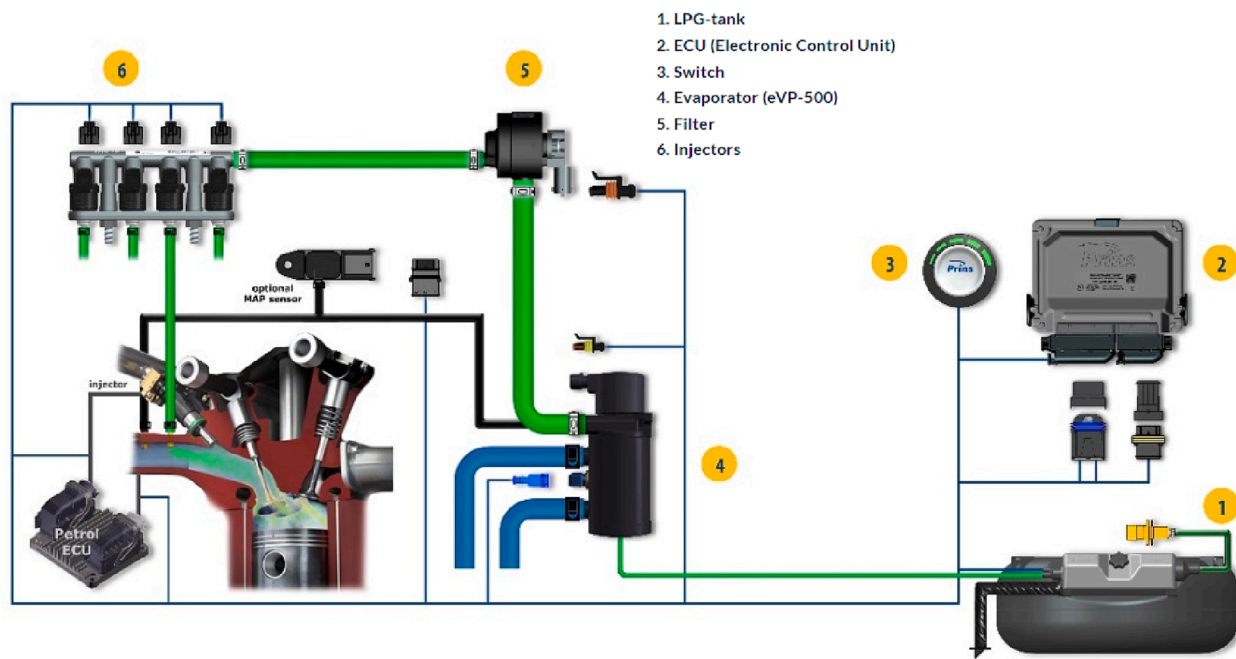


Fig. 2. Gas phase LPG system [25].

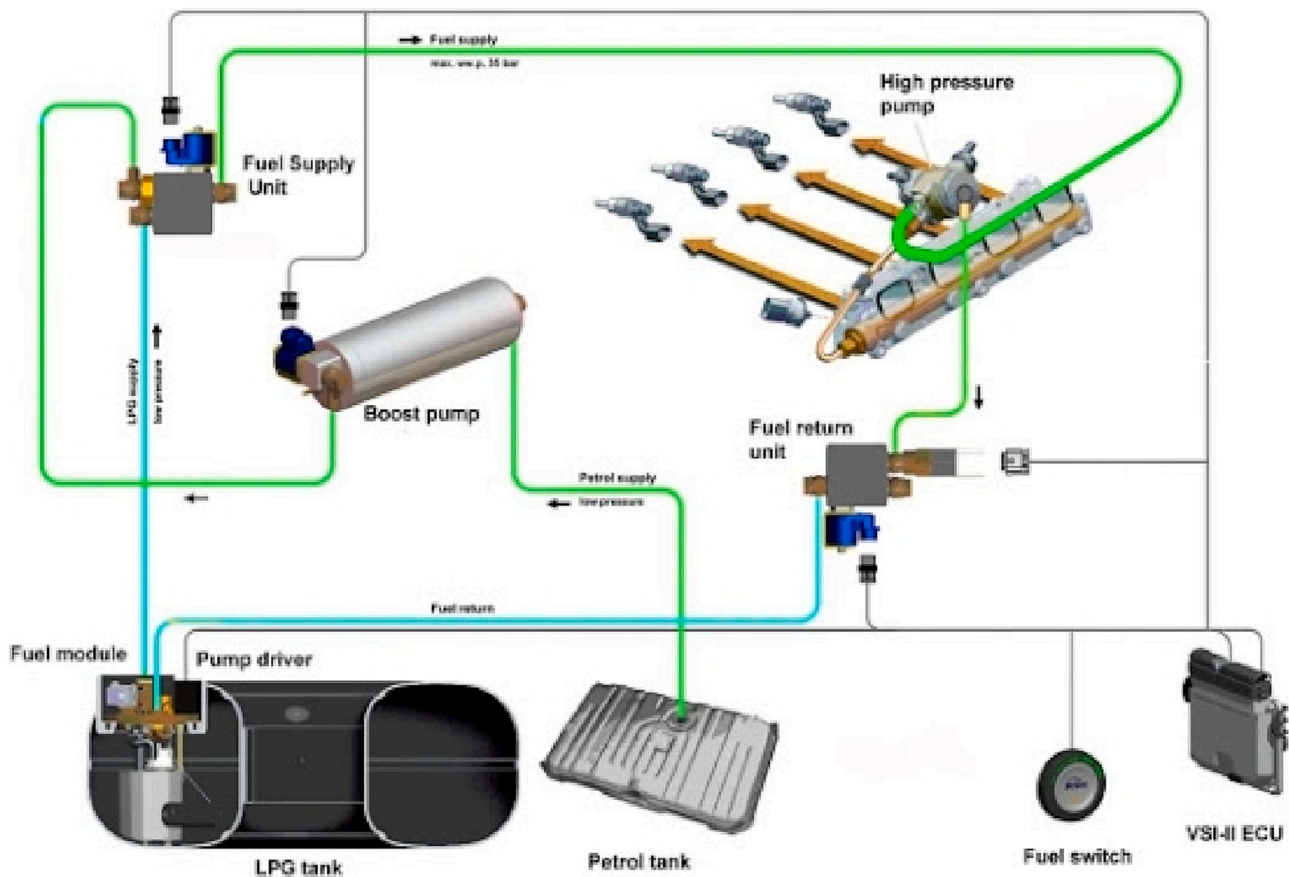


Fig. 3. Liquid DI-TSI LPG system [26].

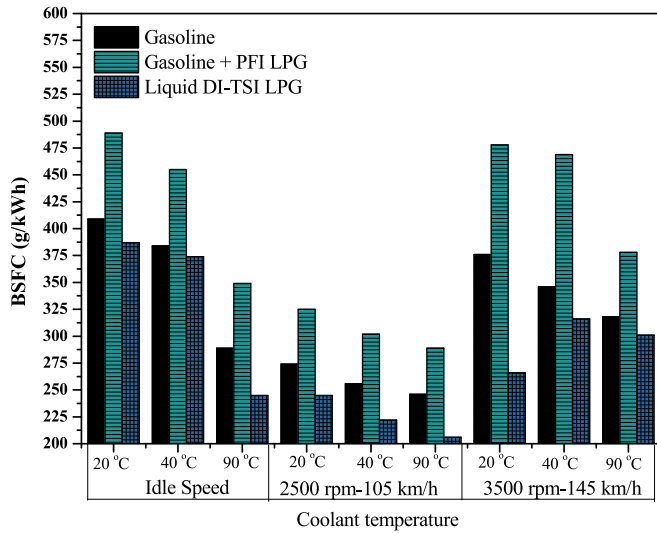
temperature conditions are given in Fig. 8. The highest HC emission occurred with 20 °C engine coolant temperature and a liquid DI-TSI LPG system. The lowest HC emission occurred with 90 °C engine coolant temperature and a liquid DI-TSI LPG system at 3500 RPM-145 km/h

vehicle speed. In addition, HC emissions decreased with the increase in engine coolant temperature for the three systems. The lowest HC emission was obtained with gasoline, while the highest was obtained from a liquid DI-TSI LPG system at 20 °C engine coolant temperature and

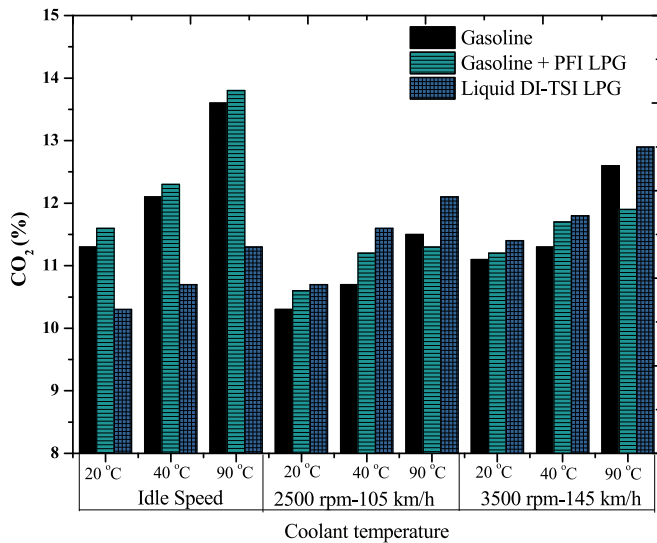
**Table 4**  
Exhaust emission device measurement parameters.

Measurement	Measurement range	Measurement Accuracy
HC	0–20000 ppm Hexan	1%
CO	0–5 %vol.	0.001%
CO <sub>2</sub>	0–20 %vol.	0.1%
NOx	30–10000 ppm	±1 ppm

\* MID (2014/32/UE), OIML R 99, ISO 3930, BAR97 (bench).

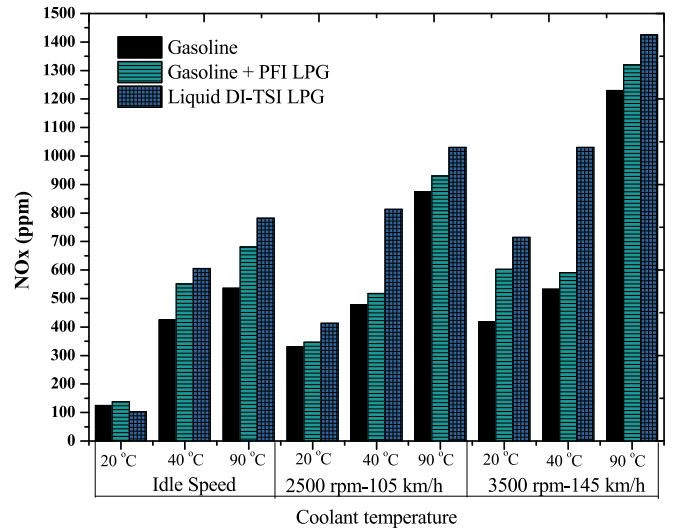


**Fig. 4.** BSFC change at different vehicle speeds and engine coolant temperatures.

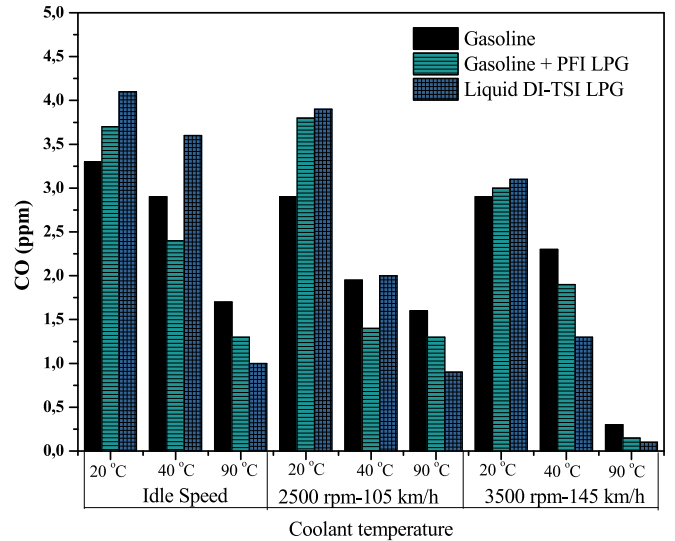


**Fig. 5.** Change of CO<sub>2</sub> emission at different vehicle speed and engine coolant temperatures.

all vehicle speeds. The lowest HC emission was obtained with gasoline and the highest with the liquid DI-TSI LPG system at 20 °C engine coolant temperature. This situation was reversed with the increase in engine coolant temperature. In other words, the highest HC emission was obtained with gasoline, and the lowest HC emission was the liquid DI-TSI LPG system at 40 °C and 90 °C cooling water temperatures.



**Fig. 6.** Change of NOx emission at different vehicle speed and engine coolant temperatures.



**Fig. 7.** Change of CO emission at different vehicle speed and engine coolant temperatures.

**4. Conclusions**

In this study, cold working performances of gasoline, a liquid DI-TSI LPG and gasoline + PFI LPG systems in a T-GDI engine were compared at different coolant temperatures and vehicle speeds. Experiments were carried out with a vehicle and a chassis dynamometer. It has been observed results as given in the following points;

- 1) Increasing the coolant temperature decreased the BSFC for all fuel mixtures and vehicle speeds. It has been determined that the vehicle with the liquid DI-TSI LPG system provides a lower fuel consumption performance than the gasoline + PFI LPG.
- 2) Especially the liquid DI-TSI LPG and the gasoline + PFI LPG systems produce more HC and CO emissions than gasoline during cold working. Although the vehicle speed increases, it can be said that gasoline is more advantageous in terms of HC and CO emissions in engine-cold conditions. However, it can be said that the liquid DI-TSI LPG system gives the best HC and CO emissions with the increase in engine coolant temperature for all vehicle speeds.

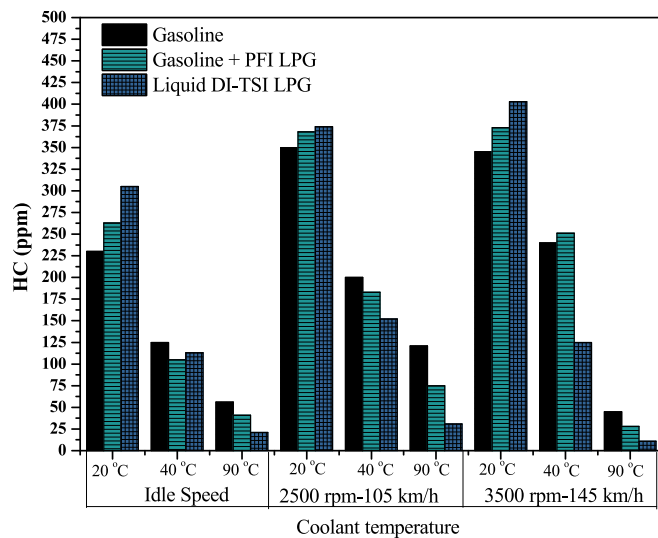


Fig. 8. Change of HC emission at different vehicle speeds and engine coolant temperatures.

- NO<sub>x</sub> formation occurred less than in the liquid DI-TSI LPG and the gasoline + PFI LPG systems. Since the maximum combustion temperature of gasoline is lower than LPG, contrary to other emissions, it was observed that NO<sub>x</sub> emissions increased with increasing engine coolant temperature and vehicle speed.
- The lowest CO<sub>2</sub> emissions were obtained with the liquid DI-TSI LPG system at idle speed in all engine coolant temperature conditions.
- According to all emission results, it will be more appropriate for the engine to run on gasoline in cold operating conditions and at idle speed. It is understood that the use of the liquid DI-TSI LPG system with the increase in engine coolant temperature will be advantageous apart from NO<sub>x</sub> emission.

It is suggested that at cold operation conditions, using gasoline and after increasing engine coolant temperature using the direct liquid DI-TSI LPG injection systems will be more advantageous in terms of emissions and fuel consumption as a dual-fuel engine.

#### CRedit authorship contribution statement

**Salih Özer:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Visualization, Supervision, Data curation, Resources, Investigation. **Usame Demir:** Writing – original draft, Writing – review & editing, Data curation, Resources. **Gokhan Coskun:** Writing – original draft, Writing – review & editing, Data curation, Resources.

#### 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.

#### Data availability

No data was used for the research described in the article.

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