energies

MDPI

Article

The Effect of Using Ethanol-Gasoline Blends on the Mechanical, Energy and Environmental Performance of In-Use Vehicles

Juan E. Tibaquirá [1], José I. Huertas [2,*], Sebastián Ospina [1], Luis F. Quirama [1] and José E. Niño [2]

[1] Mechanical Engineering Department, Universidad Tecnológica de Pereira, Pereira 660003, Colombia; juantiba@utp.edu.co (J.E.T.); sebaospina@utp.edu.co (S.O.); luisfelipequirama@utp.edu.co (L.F.Q.)

[2] School of Science and Engineering, Energy and Climate Change Research Group, Tecnológico de Monterrey, Monterrey 64849, Mexico; A01365676@itesm.mx

* Correspondence: jhuertas@itesm.mx; Tel.: +52-1-722-100-9417

Received: 12 December 2017; Accepted: 11 January 2018; Published: 17 January 2018

Abstract: The use of ethanol in gasoline has become a worldwide tendency as an alternative to reduce net CO_2 emissions to the atmosphere, increasing gasoline octane rating and reducing dependence on petroleum products. However, recently environmental authorities in large urban centers have expressed their concerns on the true effect of using ethanol blends of up to 20% v/v in in-use vehicles without any modification in the setup of the engine control unit (ECU), and on the variations of these effects along the years of operation of these vehicles. Their main concern is the potential increase in the emissions of volatile organic compounds with high ozone formation potential. To address these concerns, we developed analytical and experimental work testing engines under steady-conditions. We also tested carbureted and fuel-injected vehicles every 10,000 km during their first 100,000 km of operation. We measured the effect of using ethanol-gasoline blends on the power and torque generated, the fuel consumption and CO_2, CO, NOx and unburned hydrocarbon emissions, including volatile organic compounds (VOCs) such as acetaldehyde, formaldehyde, benzene and 1,3-butadiene which are considered important ozone precursors. The obtained results showed statistically no significant differences in these variables when vehicles operate with a blend of 20% v/v ethanol and 80% v/v gasoline (E20) instead of gasoline. Those results remained unchanged during the first 100,000 km of operation of the vehicles. We also observed that when the vehicles operated with E20 at high engine loads, they showed a tendency to operate with greater values of λ (ratio of the actual air-fuel ratio to the stoichiometric air-fuel ratio) when compared to their operation with gasoline. According to the Eco-Indicator-99, these results represent a minor reduction (<1.3%) on the impact to human health, and on the deterioration of the ecosystem. However, it implies a 12.9% deterioration of the natural resources. Thermal equilibrium analysis, at the tailpipe conditions (~100 °C), showed that ethane, formaldehyde, ethylene and ethanol are the most relevant VOCs in terms of the amount of mass emitted. The use of ethanol in the gasoline reduced 20–40% of those emissions. These reductions implied an average reduction of 17% in the ozone formation potential.

Keywords: E10 and E20; ozone formation potential; vehicular emissions; volatile organic compounds (VOCs) emissions in vehicles; eco-indicator

1. Introduction

Currently, road transport is the largest consumer of petroleum-derived fuels in the world (~25%), and therefore it is the main emitter of atmospheric pollutants in urban centers (>75%) [1]. Due to the growing energy demand, the increasing fuel prices, the severe air pollution issues in city centers, and the more restrictive environmental regulations to the road transport sector, nations worldwide are vigorously developing and finding alternative fuel sources and new technologies to reduce the vehicular emissions of air pollutants [2,3].

Ethanol is a fuel produced mainly from crop materials such as sugarcane and corn, which makes it an attractive substitute for gasoline for reducing dependence on fossil fuels and reducing CO_2 net emissions released into the atmosphere. Additionally, ethanol has a higher octane number than gasoline (~108.5 vs. 84.4, Table 1) [4] which implies that ethanol-gasoline blends have a higher octane number than traditional gasoline. Therefore, the use of ethanol becomes a partial alternative for providing high-octane fuels (~94), required for modern high compression ratio engines. As the efficiency of engines increases with the engine's compression ratio, which demands a fuel with a high octane number, the use of ethanol in an engine can improve the energy efficiency [5]. Ethanol is also characterized by having a higher heat of vaporization than gasoline (Table 1). This aspect makes the temperature of the intake manifold lower, which increases air-fuel mixture density, therefore increasing the engine's volumetric efficiency. However, a higher heat of vaporization also causes lower combustion temperatures and burning velocities, which could potentially cause higher CO and HC emissions. The Reid Vapor Pressure (RVP) of ethanol is much lower than that of gasoline (Table 1), and the resulting lower volatility reduces the VOCs emissions during pumping processes. However, it can also cause difficult cold transient of the engine during the warm-up phase. The ethanol-gasoline blended fuel does not have an RVP value that ranges linearly with the percentage of ethanol in the blends. In fact, the RVP of the blended fuel rises with the ethanol content until reaching a maximal value at around 15% *v*/*v* of ethanol addition [6]. At higher ethanol percentages, the RVP declines. Finally, the energy content of ethanol is approximately one third lower than that of gasoline (Table 1). Thus, the combustion temperature is lower which reduces the formation of NOx. However, the heating value of the ethanol-gasoline blended fuel will decrease with the ethanol content and therefore more mass of fuel will be required to obtain the same engine power output [2].

Table 1. Properties of ethanol-gasoline blends.

Property	Method/References	Gasoline	E10	E20	E100
Density (kg/m^3)	ASTM D369	733	739	746	790.7
LHV (kJ/kg)	[7]	43000	41282	39591	26950
Latent Heat of Vaporization (kJ/kg)	[8]	305	-	-	840
RVP (kPa)	ASTM D323	62	-	-	14
RON	ASTM D2699	88.5	90.7	94.8	115
MON	ASTM D2700	80.3	81.6	83.3	102
AKI	(RON + MON)/2	84.4	86.2	89.1	108.5
Stoichiometric air/fuel ratio	-	14.49	13.89	13.31	8.87

Many authors have studied the performance of spark-ignition engines on engine-dynamometers, when they operate with ethanol-gasoline blends, controlling the fuel-air ratio, under steady-state conditions. These studies have found that the use of blends with low concentrations of ethanol (<20% *v*/*v* ethanol) have a negligible effect on the power and torque generated by the engine [9–11]. Likewise, a negligible effect on CO_2 emissions and a slight reduction on CO, NOx and HC emissions has been found [4,9,12,13]. However, the validity of these results is limited to the particular conditions under which the tests were carried out and by the reduced number of engines tested. Furthermore, conclusions drawn from testing engines under laboratory conditions are not necessarily the ones expected for new and in-use vehicles, when they circulate in the city operating with ethanol-gasoline blends without any previous adjustment in the programming of their respective engines. The effect of using ethanol-gasoline blend on carbureted and fuel-injected vehicles for a long period of time (>10,000 km) has not been studied yet either.

Recently, it was reported that the use of ethanol-gasoline blends in vehicles increases the emission of volatile organic compounds (VOCs) [2], especially acetaldehydes compounds, which are precursors of tropospheric ozone in urban areas. This contradictory result has reversed the decision of government authorities, previously in favor of the use of ethanol-gasoline blends in large urban centers such as Mexico City, where the main environmental problem is the high concentration of tropospheric ozone. An analytical study is required to explore if this result is a natural tendency of the ethanol-gasoline-air combustion process inside the engine or a particular result.

To address these issues, we studied analytically and experimentally the effect of using low ethanol content (<20% v/v) in the mechanical and environmental performance of in-use sedan-type gasoline fueled vehicles, without any prior adjustment to the programming of the engine. Initially, we used a zero-dimensional model that simulates the operation of the engine and estimated the power, fuel consumption, and the generated emission of air pollutants under different working conditions. Then, we measured these variables in two engines typically used in sedan-type vehicles, under laboratory conditions at different heights above sea level. Finally, we evaluated the same variables in four vehicles every 10,000 km of operation over their first 100,000 km of operation, running under very different weather conditions and altitudes.

2. Methodology

Figure 1 illustrates the methodology implemented to evaluate the effect of using E20 on the mechanical, energy and environmental performance of in-use vehicles, operating on a daily basis under different real altitude and climate conditions. This methodology involved an analytical phase, an experimental phase testing the engines under laboratory conditions and finally an experimental phase testing the vehicles under on-road conditions. In all cases, the power generated (P), specific fuel consumption (SFC) and CO_2, CO, NOx and VOCs emission index (EI) were observed when the engine or the vehicle was fueled with gasoline and E20.

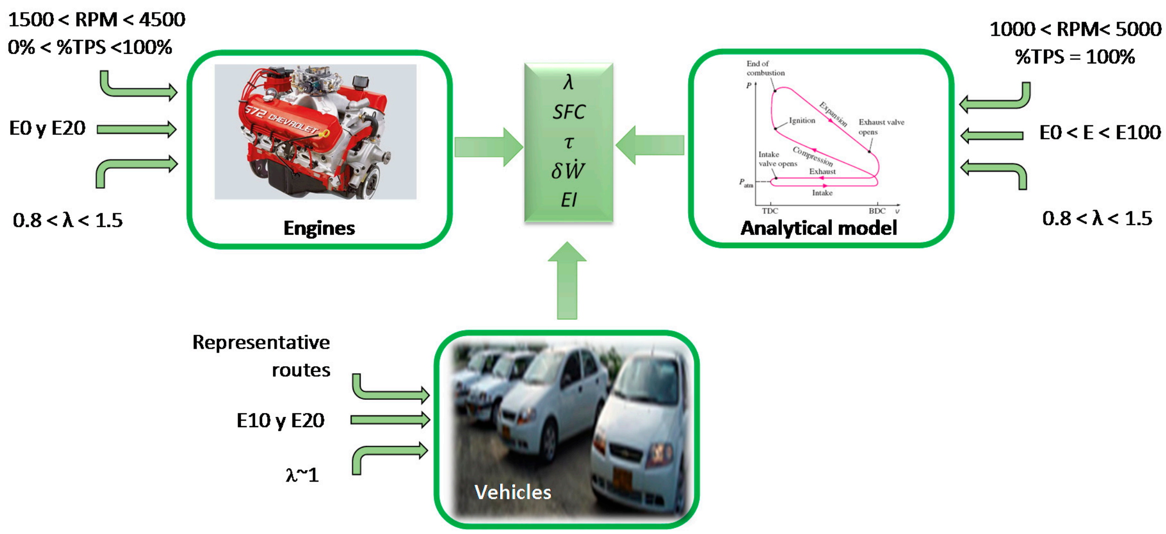


Figure 1. Illustration of the general methodology used to evaluate the effects of using ethanol-gasoline blends on the mechanical, energy and environmental performance of in-use vehicles during their useful life of operation.

2.1. Studying the Effect of Fuel Change Using a Zero-Dimensional Model for Engines

The analytical study seeks to establish the thermodynamic expected effects of using ethanol-gasoline blends on vehicles. Equations (1)–(5) estimate SFC, P, τ and EI for the given engine geometry (Ed, Nc, r) and its operating parameters (RPM, λ).

$$SFC = \frac{\dot{m}_f}{P} \quad (1)$$

$$P = \eta_{th}\, \dot{m}_f\, LHV\, \eta_m \tag{2}$$

$$\tau = \frac{60\, P}{2\pi\, RPM} \tag{3}$$

$$\dot{m}_i = x_i\, \dot{m}_f (1 + \lambda\, (A/F)_s) \tag{4}$$

$$EI_i = \frac{\dot{m}_i}{P} \tag{5}$$

To estimate the work generated per cycle (δw) and the thermal efficiency (η_{th}) of the engine, we used the CIMA model, which is a zero-dimensional steady-state model similar to the Otto cycle [7]. In the CIMA model, the combustion process is modeled through a classical chemical thermo-equilibrium analysis, which involves solving a system of nonlinear equations with as many equations of chemical equilibrium as species considered, equations for species conservation and an extra equation for energy conservation. Additionally, it considers energy losses in the compression and expansion processes through the second-law of thermodynamics efficiency concept. For estimating the mass of the pollutant i emitted at the vehicle's exhaust pipe (m_i), we calculated the thermo-chemical equilibrium composition of combustion byproducts at the temperature of the exhaust pipe.

Results of this model have shown a high correlation ($R^2 > 0.9$) with experimental results carried out on an engine test bench and on vehicles by on-road tests. The main assumptions of this model are that the working substance behaves as an ideal gas and that the equilibrium composition is reached at the temperature of exhaust gases, except for NOx, where it is assumed that the NOx mass emitted by the exhaust pipe is equal to the one formed at the end of the combustion process.

Using the CIMA model, *SFC*, *P*, τ and *EI* were estimated using the data specified in Table 2 as input data.

Table 2. Input data for estimating fuel consumption and mass emissions of air pollutants.

Parameter	Symbol	Units	Range
Ambient pressure	P_0	kPa	75
Ambient temperature	T_0	K	288
Fuel	-	-	Gasoline–E100
Compression ratio	r	-	9.4
Engine displacement	Ed	cm^3	1597
Lambda	λ	-	0.8–1.5
RPM	-	-	1000–5000

2.2. Evaluation of the Fuel Change in Engines

To include technological aspects in the evaluation of the effect that the fuel change causes in the performance of vehicles, two typical engines frequently found in sedan vehicles were evaluated. The first engine operated at 1000 masl (T_0 = 20 °C and P_0 = 87 kPa) while the second engine operated at 2400 masl (T_0 = 15 °C and P_0 = 75 kPa). In both cases *SFC*, *P*, τ and *EI* of air pollutants were evaluated on an engine test bench under steady-state conditions as a function of *RPM*, λ and engine load (inlet pressure). The tests were limited to gasoline, E20 gasoline and E20. Table 3 describes the technical characteristics of the engines.

To test engine 1 we used a Dynapack 2WD-2 cube dynamometer (oil hydraulic dynamometer, 0–2000 Nm range and 5 Nm of resolution) to measure engine mechanical performance variables, a Vgate OBD scan and a LabView homemade software interface to read engine sensors (RPM, TPS position). We used a SUM–290122 fuel tank and 6 kg Fenix Lexus electronic scale (0.5 g of resolution) for the measurement of fuel consumption. We used a Galio Smart 2000X gas analyzer to determine exhaust gas composition and an Innovate LC-1 lambda sensor for the determination of λ values (Table 4).

To test engine 2 we used a SuperFlow SF902 engine test dynamometer (hydraulic, 0–1627 Nm range, and 5 Nm of resolution, (Superflow, Des Moines, IA, USA). We measured engine operational parameters (engine RPM, temperatures, TPS position) via an ELM327 OBD scan and a LabView software interface. We measured fuel consumption in volumetric form using an auxiliary calibrated $\frac{1}{4}$-inch glass tube and a DVT Legend Vision camera. For the determination of exhaust gas composition, we used an FGA-4000XD gas analyzer (Infrared Industries, Hayward, CA, USA) (Table 4). We used an external engine Electronic Control Unit to establish the λ values of engine operation.

Table 3. Technical description of the engines used to evaluate changes in their performance when fueled with gasoline and E20.

	Engine 1	**Engine 2**
Model	Chevrolet Sail/LPDA	Chevy
Powertrain	DOHC	GM Z16SE
Displacement [cm^3]	1398	1597
Orientation	Transversal	Longitudinal
Compression ratio	10.2	9.4
Cylinder diameter/Stroke	79.8 mm/81.8 mm	-
Distribution	4 valves per cylinder/2 camshafts	2 valves per cylinder/1 camshaft
Fuel System	Indirect fuel injection	Sequential multipoint fuel injection
Power rating	76 kW @ 6000 RPM	74.5 kW @ 5600 RPM
Torque	130 Nm @ 4200 RPM	135.6 Nm @ 3200 RPM

Table 4. Technical characteristics of the instrumentation used in this work.

		Lab 1			**Lab 2**		
Dynamometer	Trademark	Dynapack 2wd-2			SuperFlow SF902		
	Range	0–2000 Nm			0–1627 Nm		
	Power capacity	300 kW			1119 kW		
	Maximum speed	2450 hub RPM			15,000 RPM		
Gas Analyzer	Trademark	Galio Smart 2000X gas analyzer			FGA 4000XD gas analyzer		
	Variable	Method	Range	Accuracy	Method	Range	Accuracy
	CO	Infrared	0–10 % V	0.06% Absolute, 5% Relative	Infrared	0–10 % V	±5%
	CO_2	Infrared	0–20 % V	0.03% Absolute, 5% Relative	Infrared	0–20 % V	±5%
	HC	Infrared	0–10,000 ppm	4 ppm Absolute, 5% Relative	Infrared	0–5000 ppm	±5%
	O_2	Infrared	0–25 % V	±2% Relative	Infrared	0–25 % V	±5%
	NOx	Infrared	0–2000 ppm	32 ppm Absolute	Infrared	0–5000 ppm	±4%
Lambda sensor	Trademark	*Innovate Motorsport LC-1*					
	Variable		Response time	Range		Accuracy	
	λ		<100 ms	0.5–8.0		±0.007	

2.3. Evaluation of the Fuel Change in Vehicles

To include all the operational aspects which have an impact on the real performance of the vehicles, we evaluated four sedan type vehicles typically used in Latin America. Two of them were carbureted vehicles (Chevrolet Sprint) and the other two had electronic fuel injection (Chevrolet Aveo). Table 5 describes the technical characteristics of these vehicles. The fuel-injected vehicles were brand new at the time tests started. Due to environmental regulations, it was not possible to obtain brand new carbureted vehicles at that time. Therefore, we purchased two two-year old carbureted vehicles and provided them with full mechanical maintenance, which included the replacement of all powertrain elements with original spare parts, except for the engine block and the transmission. The carbureted vehicles were included in this analysis because there are still a significant number of vehicles operating with this technology and the fuel change can generate big changes in their performance, to the extent that it can generate adverse changes that could frustrate the benefits pursued by the authorities in the promotion of biofuel use.

For the experiments, one fuel-injected and one carbureted vehicle operated with E10 and the other two with E20. The vehicles were subjected to normal operating conditions, always following the same routes. During the road tests, drivers were exchanged every two hours to eliminate potential deviations generated by the driving style.

The performance of the vehicles was monitored every ~10,000 km. SFC, CO, CO_2 and HC emission indices were measured when the vehicles reproduced the New European Driving Cycle (NEDC) on a chassis dynamometer. The instruments used for all tests in this case were the same as those described in Table 4 for the evaluation of engine 1 under steady-state conditions.

The properties of the fuels used during the experimental work are shown in Table 1.

Table 5. Vehicles' technical characteristics in long-term tests.

	Chevrolet Sprint 1997	Chevrolet Aveo 2010
Engine Displacement (cm^3)	990	1.598
Engine compression ratio	8.5:1	9.5:1
Weight (kg)	690	1165
Fuel System	Carburetor	Sequential multipoint fuel injection
Transmission	Manual transmission, 5 speeds	Manual transmission, 5 speeds
Power rating	37 kW @ 5100 RPM	82 kW @ 6000 RPM
Torque	77 Nm @ 3200 RPM	145 Nm @ 3600 RPM

3. Results

3.1. Power and Torque

Figure 2 shows the power generated by the vehicles when they operate with ethanol-gasoline blends.

Analytical Results: Assuming that the mechanical efficiency of the engine remains unaffected by the fuel change, the mechanical power generated by the engine decreases with the ethanol content in the fuel. When E20 is used instead of gasoline, the power generated by the engine decreases between 0.19% and 0.48% depending on λ. This decrease can be up to 2.6% when using E85 (Figure 2a). These negligible changes in power result from the compensatory effect generated by the reduction in the air/fuel ratio (A/F_{E20} = 13.31 vs. $A/F_{Gasoline}$ = 14.49) to the negative effect of the lower energy content of the ethanol (LHV_{E20} = 39,860 kJ/kg vs. $LHV_{Gasoline}$ = 43,370 kJ/kg). The engine requires less air to burn the same mass of fuel and therefore it can increase the amount of fuel injected into the combustion chamber per engine cycle, which increases the power generated during each cycle. When the engine operates with E20, it uses a fuel with 8% less energy content than when it operates with gasoline, but it can use 8.1% more fuel. The net effect is a minor reduction in power (<0.2% for λ = 1).

Experimental results obtained under steady-state conditions showed that in no operational mode of the tested engines did the power generated show statistically significant changes when E20 was used instead of gasoline. Figure 2c shows that for the case of engine 1, the average power decreased in all operating modes between 0.1% and 3.2%. However, for engine 2 (operating at 2750 masl), the average power increased between 0.1% and 8.9% in 75% of the operating modes. These results agree with analytical results that predict smaller reductions in power than the variability of the power vs. RPM experimental results. Additionally, these results agree with those obtained by other authors. Ref. [9] used blends of gasoline and E30 and found that the full-load power of a four-cylinder engine is slightly diminished (up to 3%) as the ethanol content increases in the fuel. Ref. [14] analyzed a KIA 1.3 SOHC four-cylinder engine, operating with gasoline-E20 blends at full load and found that the power increased slightly with the ethanol content in the fuel. Ref. [11] studied a 200 cm^3 mono-cylinder engine, fueled with gasoline and up to E100 and found no trend in the power generated by the engine.

Experimental results with vehicles: The tests performed on the four vehicles on the chassis dynamometer every ~10,000 km of operation showed no statistically significant differences in power when they operated with E20 instead of E10. In this case, E10 was used instead of gasoline because E10 was the only commercially available fuel in the region where tests were carried out. We also observed that the normal deterioration of the vehicles did not affect the power delivered by the engine when it operated with E10 or E20 (Figure 2d).

The torque delivered by an internal combustion engine is directly related to the power generated by the engine, through Equation (3). In fact, torque is the variable measured in the laboratory tests and power is the derived reported variable. Thus, the effect of the fuel change on this variable is similar to the one described for power. In summary, analytical and experimental results obtained on engines and in fuel-injected and carbureted vehicles showed a negligible loss of torque (<0.51%) when the engine operates with E20 instead of gasoline.

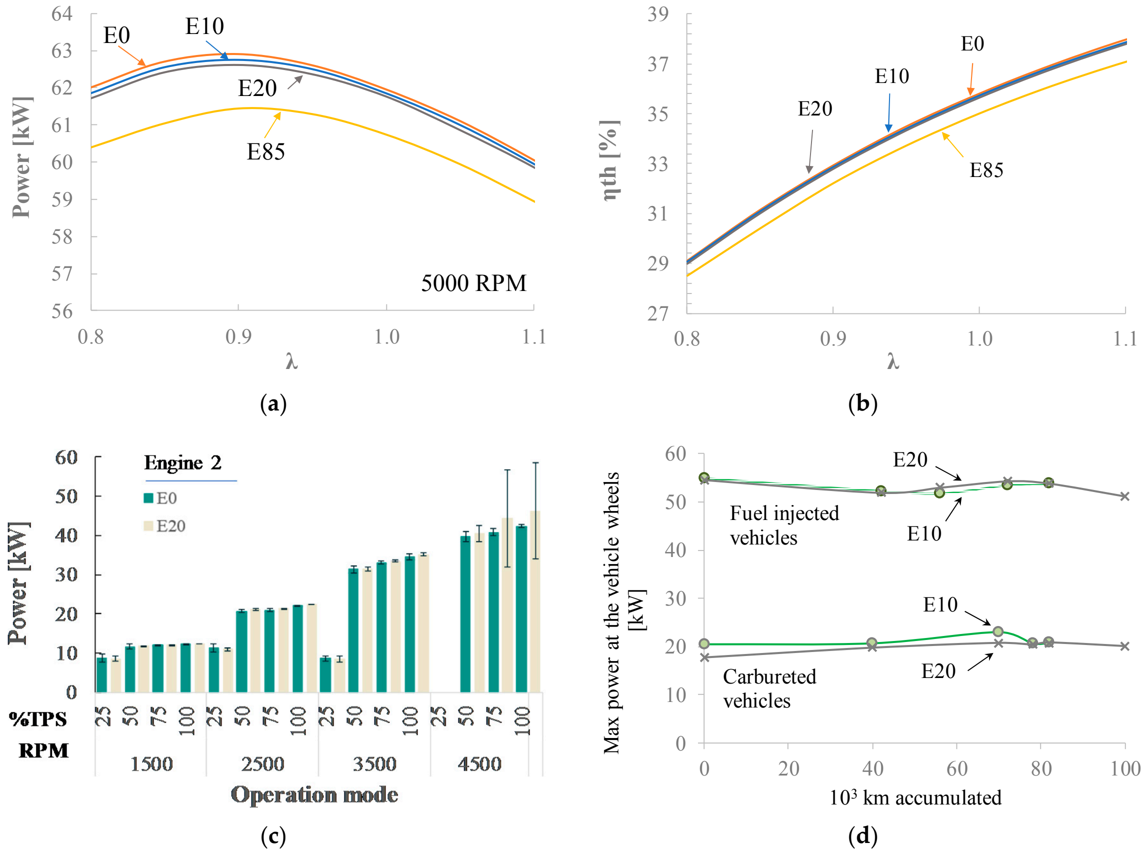


Figure 2. Power generated by engines when they operate with ethanol-gasoline blends. (**a**) Estimated power at 5000 RPM and (**b**) Estimated thermal efficiency displayed by engine 2 as a function of λ and ethanol content in the fuel; (**c**) Measured power delivered by engine 2 under steady-state conditions and different modes of operation; (**d**) Measured maximum power delivered by carbureted vehicles and fuel-injected vehicles after each ~10,000 km of operation.

3.2. Fuel Consumption

In practice, users perceive fuel consumption as volumetric consumption instead of mass fuel consumption ($\dot{m}_f$), the latter being a more appropriate variable when referring to blends. However, given that the density of gasoline (~733 kg/m^3) is similar to that of ethanol (~791 kg/m^3), differences in the fuel consumption perceived by users can be observed as differences in mass fuel consumption. The automotive community prefers to use specific fuel consumption (SFC), which is defined by Equation (1). As described above, when the ethanol content in gasoline increases, power decreases negligibly. Therefore, variations in fuel consumption can be appreciated in the same way, using volumetric consumption, mass consumption or SFC.

Figure 3a shows estimated SFC as a function of λ and ethanol content in the fuel. As described above, increasing the ethanol content in gasoline, power decreases negligibly thanks to an increase in fuel consumption that can reach up to 46.7% in the case of E85. The above effect is observed in SFC as an increase of ~9.6% for E20 and of ~52% for E85.

SFC is also a measurement of thermal efficiency when multiplied by the equivalent heating value of the fuel. Figure 2b shows that the reduction in the energy content of the fuel also generates small losses in the thermal efficiency of the engine (0.38–0.46% for E20 depending on λ). This loss in thermal efficiency increases with ethanol content, up to 2.3% for E85. Our analytical model predicts that this efficiency does not depend on engine RPM nor on engine load.

Figure 3b shows that SFC increased between 2.3% and 23.6% when engine 2 was tested using E20 instead of gasoline.

Figure 3c shows the SFC of the four vehicles operating under steady-state conditions at full load on the chassis dynamometer after 72,000 km of operation. This figure shows the typical behavior of internal combustion engines, which exhibit higher efficiencies (lower consumption) in intermediate ranges (2500–3500) of RPM. It also shows that fuel-injected vehicles are substantially more efficient than carbureted vehicles. Finally, it shows that in the case of fuel-injected vehicles, fuel consumption increased with ethanol content except at high RPM (>5000). In the case of carbureted vehicles, there was no clear trend.

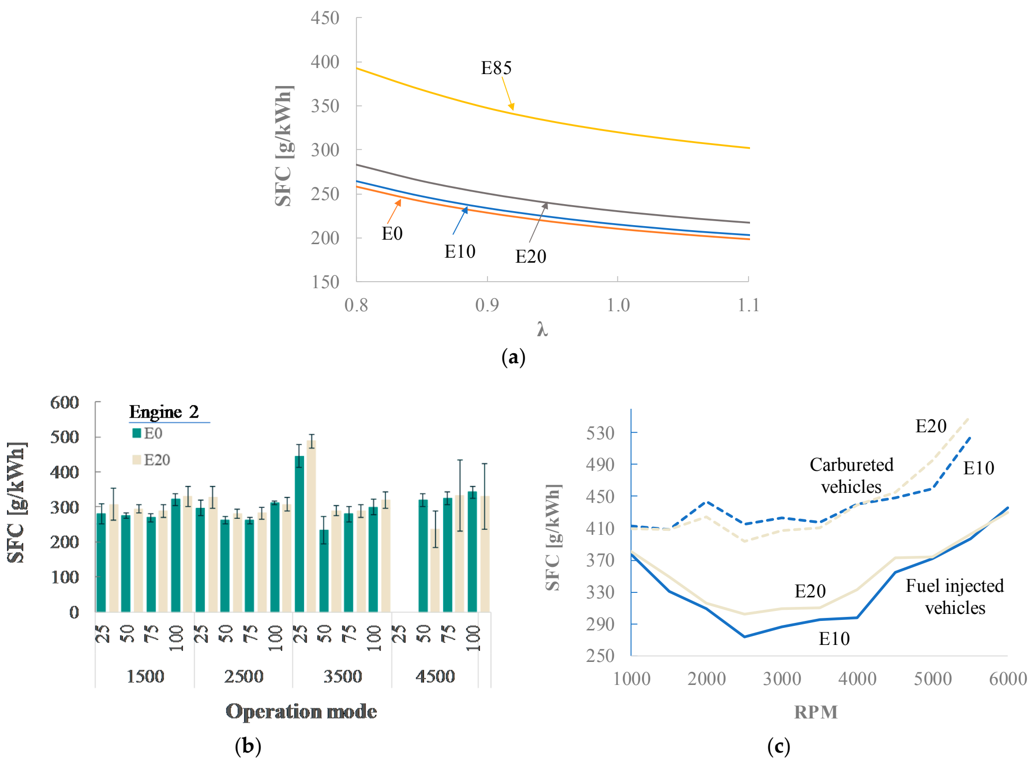


Figure 3. Results of specific fuel consumption (SFC) obtained: (**a**) analytically; (**b**) testing engine 2 under steady-state conditions; and (**c**) carbureted and fuel-injected vehicles under steady-state conditions at full load on the chassis dynamometer after 72,000 km of operation.

3.3. Effect of Fuel Change on λ

Fuel-injected vehicles usually use a lambda sensor to close the control loop of engine operation. It measures the oxygen content of the combustion products and the engine computer unit converts that measurement into a λ value using a default fuel composition. We evaluated the effects of the fuel change on the real values of λ under which the vehicles operate. To do so, we used several experimental data points of known byproducts composition and used our analytical model based on equilibrium analysis, in the reverse direction, and calculated λ, assuming that the fuel was gasoline and repeated the calculation assuming that the fuel was E20. We found differences smaller than 1% in all cases. We also compared those calculated values of λ with the ones reported by the engine computer and a third lambda sensor (Table 4). Again, we obtained negligible differences. These results indicate that lambda sensors for gasoline-fueled vehicles are unaffected when they operate with E20 instead of gasoline.

We then used the external lambda sensor described in Table 4 to compare the λ operational conditions of the vehicles when they are fueled with E20 and E10 under different steady-state conditions and we found no significant differences. However, we did find consistent differences when the vehicles operated at full load. Figure 4 shows that at full load, carbureted and fuel-injected engines operate with $0.9 < \lambda < 0.95$. It also shows that, at full load, engines tend to operate with greater values of λ when they are fueled with E20 instead of E10. This is due to the fact that at full load (maximum power), engines demand maximum fuel rates. However, when the engines operate with E20 instead of E10 they require additional fuel, as described above, but injectors, or the calibrated orifices of the carburetor, are rated for the base case of gasoline and therefore they are unable to supply the new demanded fuel rate. Consequently, the engine works with less fuel than demanded, i.e., the engine operates with greater λ than demanded. The differences disappear for lower engine loads. This fortunate fact favors the environmental performance of the vehicles, especially in the working modes where the engine is programed to work with $\lambda < 1$, that correspond to the conditions under which the emission of pollutants are the greatest, as it will be shown in the next sections.

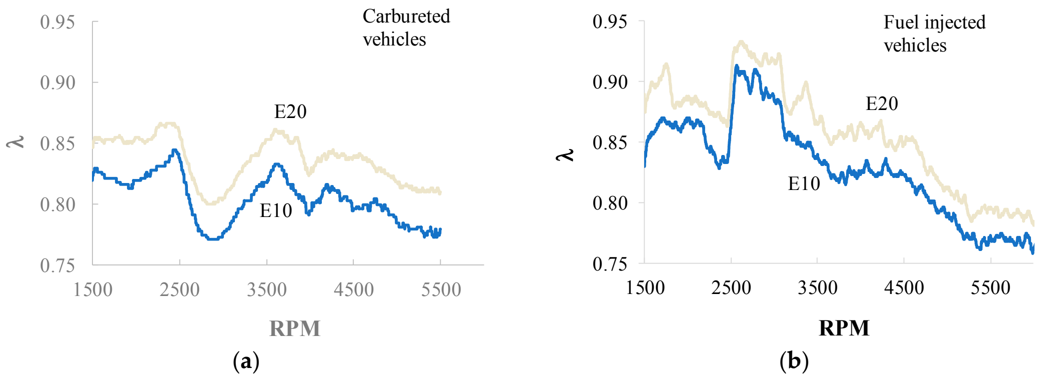


Figure 4. Effect of fuel changes in the operational conditions under which the vehicles work. λ vs. RPM obtained from (**a**) carbureted and (**b**) fuel-injected vehicles at full load.

Combustion of gasoline-ethanol blends requires a smaller amount of air than in pure gasoline combustion. For a given engine RPM and throttle valve opening, the airflow rate entering the cylinders remains the same. To keep the air-fuel equivalent ratio constant, the ECU (electronic control unit) increases the ethanol-gasoline blend rate. However, in some fuel-rich conditions, the leaning effect produced by the oxygen content of ethanol leads back to stoichiometric operating conditions, amending the combustion efficiency.

3.4. CO_2 Emission Index

Figure 5a shows that the estimated emission index for CO_2 (EI_{CO_2}) increases negligibly with ethanol content for $\lambda > 1$. EI_{CO_2} increases between 0.22% and 1.65% depending on λ when the engine operates with E20 instead of gasoline. This increase can reach up to 9% in the case of E85. Analytically, EI_{CO_2} is independent of RPM or engine load.

We found that in 93% of the engine operating modes, EI_{CO_2} showed a statistically significant increase when the engine operated with E20 instead of gasoline. This increase varied between 6.4% and 21.1% as shown in Figure 5b. This could be due to the fact that ethanol-gasoline blend ensures more efficient and complete combustion of such blends inside the cylinder, thereby increasing the total quantity of CO_2 exhaust emissions.

The increase in EI_{CO_2} was not statistically significant when carbureted and fuel-injected vehicles were evaluated following the NEDC on a chassis dynamometer, after every 10,000 km traveled. The normal deterioration of the vehicle did not affect EI_{CO_2} when they operated with E20 or E10 (Figure 5c).

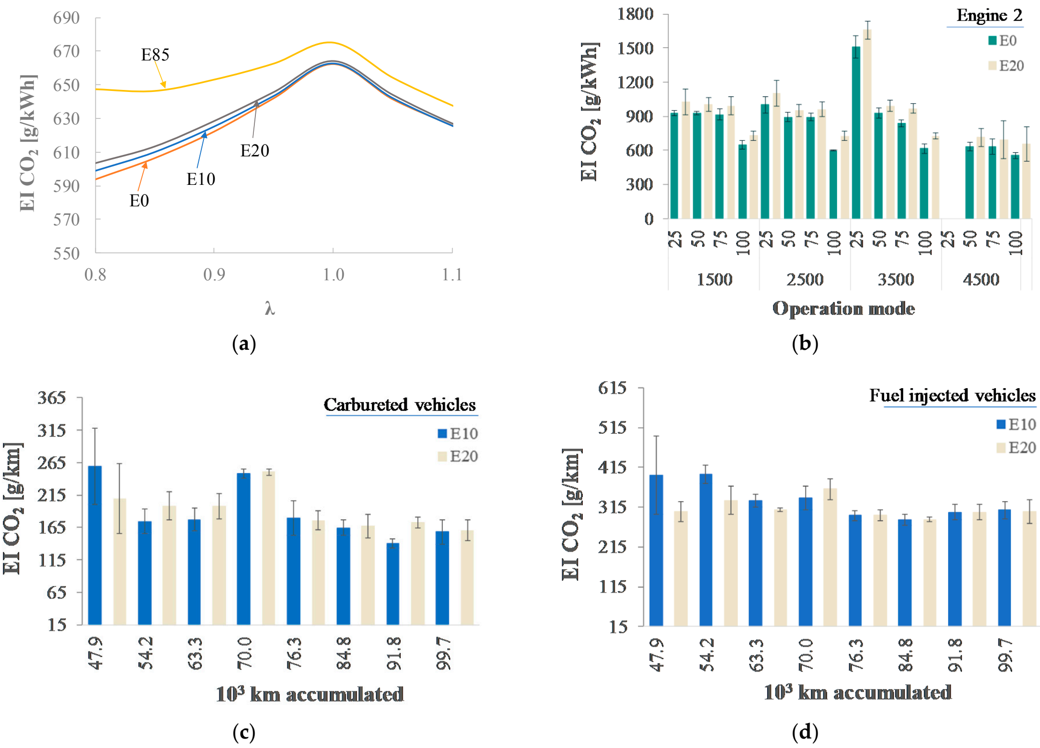


Figure 5. CO_2 emission indexes obtained through: (**a**) Analytical model; (**b**) Engine tests under steady-state conditions; (**c**) Carbureted and (**d**) Fuel-injected vehicles, following the new european driving cycle (NEDC) on chassis dynamometers, after every 10,000 km traveled.

3.5. CO Emission Index

Figure 6a shows that EI_{CO} is negligible for $\lambda > 1$ and grows proportionally with $(1 - \lambda)$. For rich air-fuel mixtures ($\lambda < 1$), the estimated EI_{CO} shows a small reduction with the ethanol content in the fuel that could be up to ~17.5% for E20.

Experimental tests on engines, operating under steady state conditions, showed that the average values of EI_{CO} tended to decrease in most of the operational modes (~80% of the cases) of the engine when they used E20 instead of gasoline (Figure 6b). However, those changes were not statistically significant. This result agrees with our analytical results and those obtained by other authors [14–16]. Figure 6c,d show that EI_{CO} is about two orders of magnitude higher for carbureted vehicles than for fuel-injected vehicles, when they reproduce the NEDC on a chassis dynamometer. This result demonstrates the capacity of fuel injection technology to control air/fuel ratio under very diverse conditions of operation in contrast to the carbureted technology.

We also found that in 88% of the evaluated cases, carbureted vehicles showed a significant reduction in CO emissions (~70%), when they used E20 instead of E10, which was an expected result given the high levels of CO emissions of carbureted vehicles and the expected effects of oxygenating the fuel with ethanol. However, in the case of fuel-injected vehicles, no statistically significant differences were observed due to fuel changes. The same results were observed during the tests carried out every ~10,000 km.

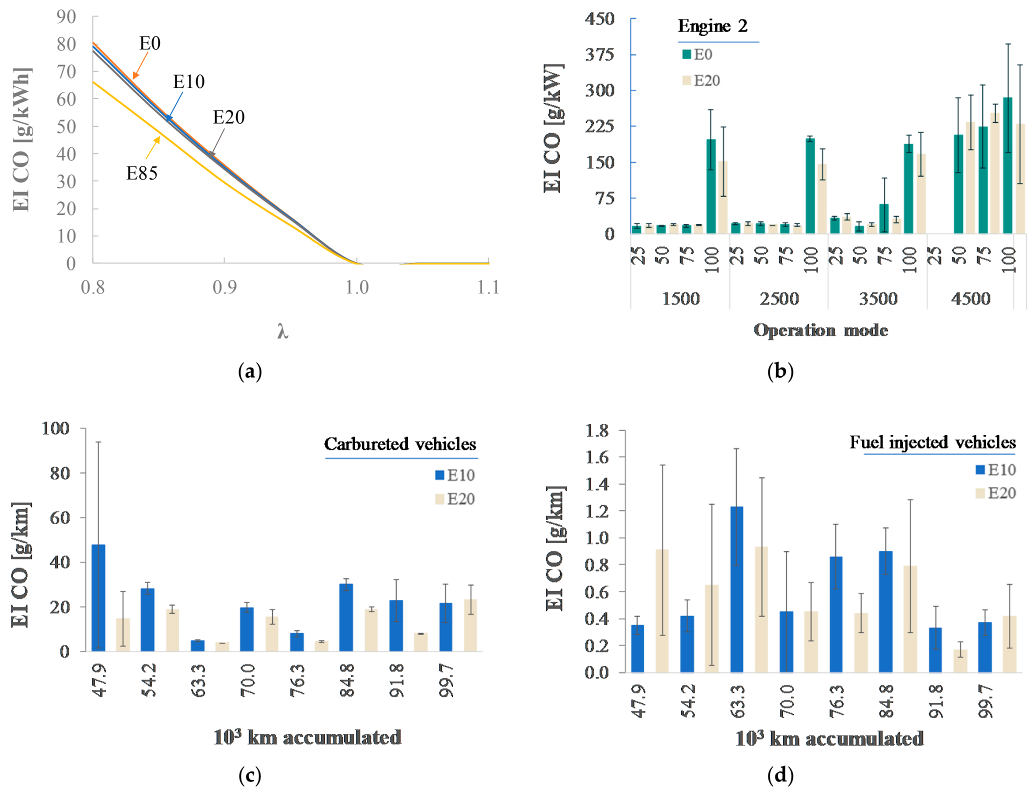


Figure 6. CO emission indexes obtained by: (**a**) Our analytical model for engines; (**b**) Engine tests under steady-state condition; (**c**) Carbureted and (**d**) Fuel-injected vehicles following the NEDC on chassis dynamometers, after every 10,000 km traveled.

3.6. NOx Emission Index

Increasing the percentage of ethanol increases the latent heat of vaporization of the blends and therefore the temperature of the air-fuel mixture decreases at the end of the intake stroke in comparison with gasoline. It also reduces the energy content of the fuel blend, which reduces the combustion temperature, reducing the thermal NOx production.

Our model for the estimation of emissions in engines predicts a small (<2.50%) reduction in the NOx emission index (EI_{NOx}) when the engine operates with E20 instead of gasoline. Figure 7a shows that this reduction can be up to 14.1% when the engine operates with E85. The formation of NOx in internal combustion engines depends strongly on the maximum temperature achieved inside the combustion chamber. Therefore, reduction in NOx emissions is due to ethanol's lower heating value, which generates lower temperatures inside the combustion chamber as ethanol content in the fuel increases.

However, engine tests showed that NOx emissions did not exhibit statistically significant changes when E20 was used instead of gasoline in any mode of operation. Figure 7b shows reductions in the average values of EI_{NOx} in the 86.7% of the modes of the engine operation. Those reductions varied between 3.0% and 17.5%. A similar result was found for the case of the carbureted and fuel injected vehicles in their test every ~20,000 km of operation. These experimental results are consistent with the results of the analytical model, which predicts NOx reductions that are lower than the variability of the experimental results. Additionally, they agree with results reported by several authors who tested engines varying the ethanol content in the fuel [4,17,18].

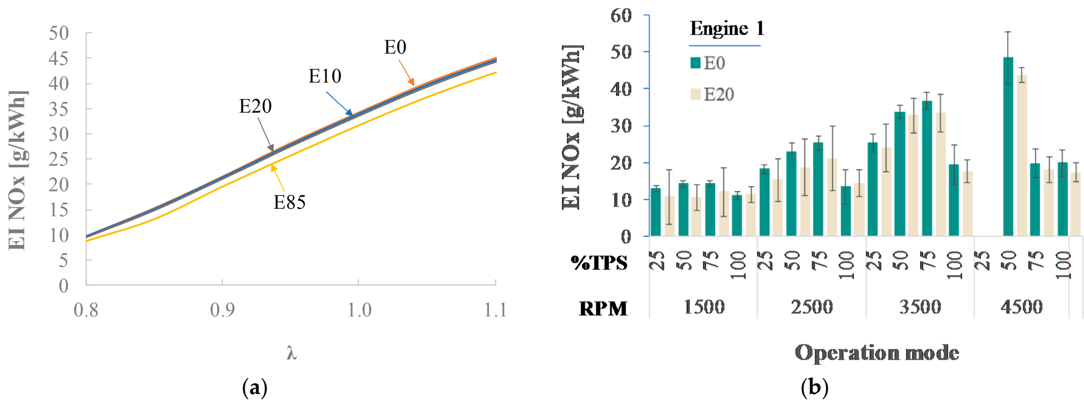


Figure 7. NOx emission indexes obtained by (**a**) Our analytical model for engines; and (**b**) Tests on engine 1 under steady-state conditions, when the engine used different ethanol-gasoline blends.

3.7. HC Emission Index

Figure 8a shows the unburned hydrocarbons emission index (EI_{HC}) estimated by thermal equilibrium analysis at the tailpipe conditions (T = 120 °C, P = 101 kPa). Results are similar to the ones obtained for CO. Like CO, EI_{HC} becomes negligible for poor air-fuel mixtures ($\lambda > 1$). However, under this operating condition, Figure 8a shows that EI_{HC} increases negligibly (~0.2%) with ethanol content in the fuel. For rich air-fuel mixtures ($\lambda < 1$), EI_{HC} increases proportionally with λ reductions. However, contrary to CO emissions, the addition of ethanol in gasoline contributes to an increase of EI_{HC} of up to 3.01% for E20 at λ = 0.85. This increase can reach up to 14.6% when operating with E85 for this same condition of extreme operation. Usually spark-ignition engines operate with λ close to 1. Results shown in Figure 8a are independent of RPM and of the percentage of engine load.

Experimental work was limited to the measurement of the unburned hydrocarbons in vehicles following the NEDC on a chassis dynamometer. We found that carbureted and fuel-injected vehicles did not show any statistically significant difference in unburned hydrocarbon emissions when vehicles were fueled with E20 compared to when they were fueled with E10 (Figure 8b,c). These experimental results are consistent with results obtained from the analytical model and with results reported by other authors [19,20].

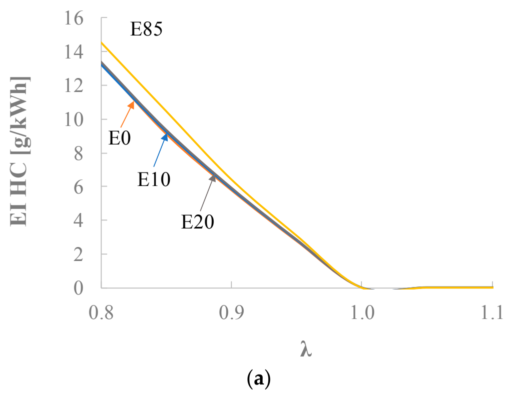
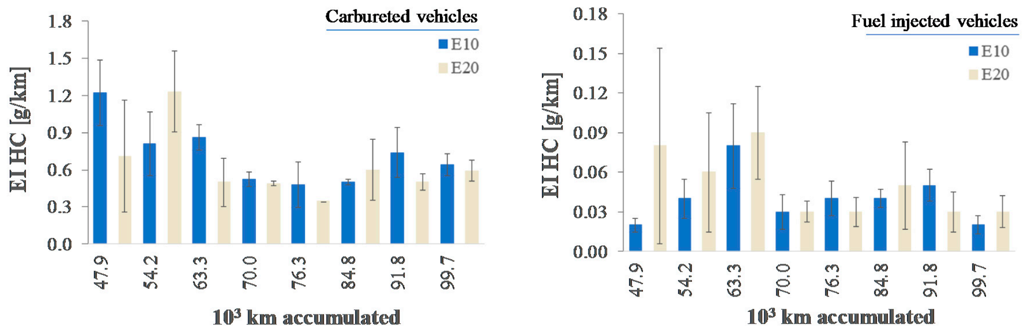


Figure 8. *Cont.*



(**b**) (**c**)

Figure 8. HC emission indexes obtained from (**a**) Our analytical model for engines; (**b**) Carbureted and (**c**) Fuel-injected vehicles following the NEDC on a chassis dynamometer every 10,000 km of operation.

3.8. Effect on the O_3 Formation Potential

As described in the introduction section, the potential increase in the emission of unburned hydrocarbons of vehicles when they are fueled with ethanol-gasoline blends instead of gasoline is an issue of great interest because unburned hydrocarbons, specifically the volatile organic compounds (VOC), are precursors of tropospheric ozone (O_3).

Figure 9a shows the equilibrium composition of most relevant VOCs at the tailpipe temperature (~100 °C). It shows that the emissions of ethane, formaldehyde, ethylene and ethanol are the most relevant VOCs in terms of the amount of mass emitted. For poor air-fuel mixtures ($\lambda > 1$) all VOCs disappear and for $\lambda < 1$ those emissions are negligible ($EI < 10^{-6}$ g/kWh). However, it is relevant to understand the tendency in the emission of VOCs to predict the potential cumulative impact of the millions of vehicles running in large urban centers.

Figure 9b shows the relative differences in those emissions when the engine operates with E20. It shows that these emissions reduce by between 20% and 40%. Toluene, benzene and 1,3-butadiene are the VOCs that experience the largest reductions in mass emissions. These equilibrium-based results do not explain the observed increases in some VOCs, particularly acetaldehydes, ethanol and formaldehydes [19]. Additional research work is needed to find out if these differences are due to the portential roll of chemical kinetics in the VOCs' concentrations or the particular conditions under which the experimental measurements were conducted.

Every VOC has a different contribution to the total ozone formation potential (OFP) of the engine emissions. The maximum incremental reactivity (MIR) index developed by Carter [21] is one of the well accepted alternatives to grade their contribution. This reactivity scale is based on calculations of relative O_3 impacts, expressed as the mass of the maximum additional O_3 formed per mass of VOC added to the emissions (g O_3/g VOC) for various compounds, under conditions in which the ambient O_3 concentration is most sensitive to changes in VOC emissions [22]. Equation 6 calculates the total OFP in g O_3/kW h of the VOCs emitted by the engine, where MIR_i is the MIR (in g O_3/g VOC_i) and EI_i is the emission index (in g VOC_i/kWh) for compound *i*.

$$\mathrm{OFP} = \sum MIR_i EI_i \tag{6}$$

Figure 9c shows the relative differences in OFP of the engine emissions when they operate with E20 instead of gasoline. It shows that for all engine operating conditions, the use of ethanol-gasoline blends tend to reduce the OFP of the engine emissions when the engine works with $\lambda < 1$, regardless of the temperature being considered.

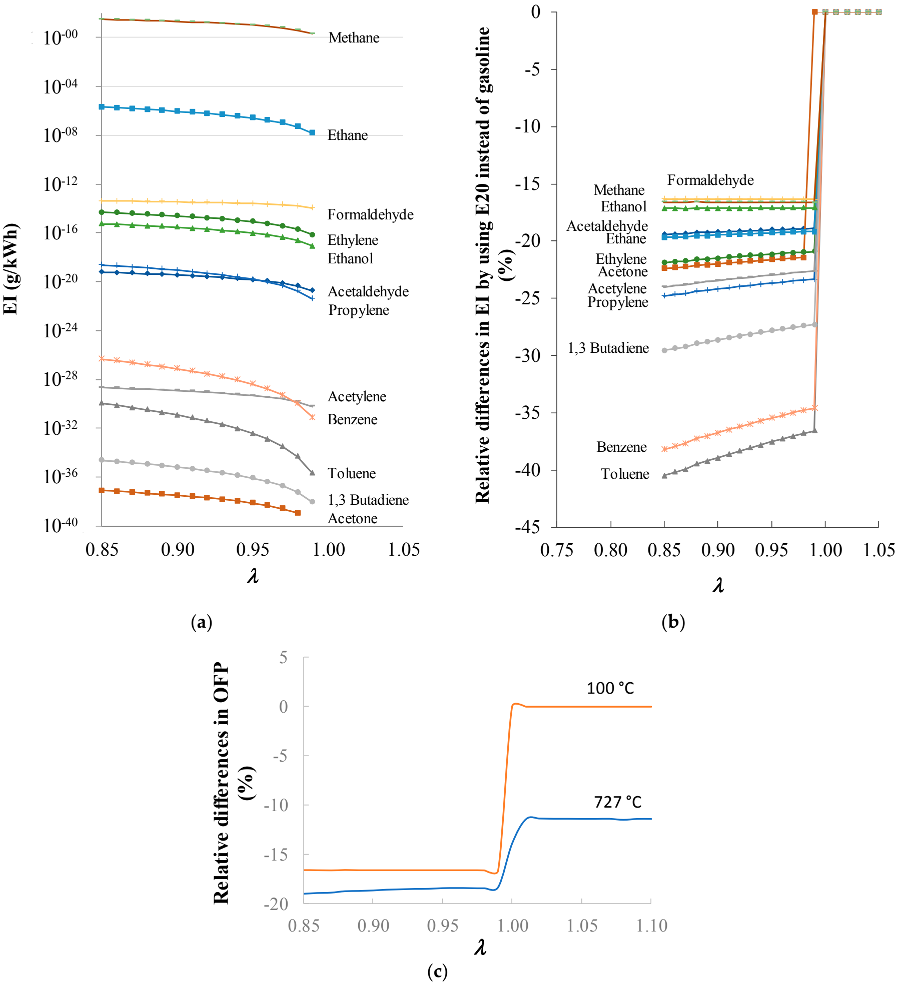


Figure 9. (**a**) Estimated emission indexes for the most relevant volatile organic compounds (VOCs) for gasoline and E20 fueled vehicles. Relative differences of using E20 instead of gasoline in (**b**) emission indexes and (**c**) ozone formation potential.

3.9. Overall Environmental Impact of Using Ethanol-Gasoline Blends in Vehicles

So far, we have described the effects of using ethanol-gasoline blends on the vehicle performance. Complementarily, it is of interest to estimate the net effect of the fuel change on the environment through a life cycle analysis. To do so, we used the Eco-indicator-99 methodology [23]. This indicator considers three areas of impact of a given process (Table 6):

- *Damage to human health*, which is given in terms of inactivity days per year caused by each kg of pollutant emitted during the process. It considers carcinogenic and respiratory effects, health effects caused by ionizing radiation, health effects caused by ozone layer depletion and damage to human health caused by climate change.
- *Damage to ecosystem quality*, which is expressed as the percentage of species that have disappeared per unit area due to the environmental loads imposed by the process. It includes toxicity, acidification, eutrophication, land-use and land transformation.
- *Damage to resources* caused by extraction of minerals and fossil fuels expressed in terms of the energy needed per unit of mineral or fuel extracted.

Medical and ecological studies have quantified and reported each of these damages for different processes. To quantify the net effect on the environment of fueling vehicles with ethanol-gasoline blends instead of gasoline, we applied the Eco-indicator-99 methodology to both cases considering the following processes: (i) The production of gasoline and E20 and (ii) The use of those fuels in vehicles.

Following this procedure, we obtained relative reductions of 1.3%, 1.4% and 12.9% in damages to human health, the ecosystem and natural resources, respectively, when using E20 instead of gasoline in vehicles. These results were expected, as emission indexes and fuel consumption were similar with E20 and gasoline. Therefore, the main contribution to the global environment of using E20 in vehicles is the reduction in the depletion of natural resources.

Table 6. Overall environmental impact of using ethanol-gasoline blends in vehicles according to the Eco-indicator-99 methodology.

Categories	Subcategories	Gasoline	E20	Reductions
Damage to human health	Carcinogenic effects	4.13×10^{-21}	4.16×10^{-21}	−1%
	Respiratory effects due to organic emissions	4.78×10^{-12}	5.38×10^{-12}	−12%
	Respiratory effects due to inorganic emissions	6.49×10^{-2}	6.39×10^{-2}	1%
	Damage to human health caused by climate change	3.50×10^{-3}	3.52×10^{-3}	−1%
Damage to ecosystem quality	Toxic emissions	2.82×10^{-46}	2.72×10^{-46}	4%
	Acidification and eutrophication	1.25×10^{-2}	1.24×10^{-2}	1%
Damage to resources	Extraction of minerals and fossil fuels	1.03×10^{-1}	8.99×10^{-2}	12%
	Fuel processing	3.57×10^{-2}	3.06×10^{-2}	14%

4. Conclusions

We performed analytical and experimental work on engines and vehicles to evaluate the effect of using ethanol-gasoline blends instead of gasoline on the mechanical, energy and environmental performance of carbureted and fuel-injected, in-use vehicles, without any adjustment in the setup of the engine computer unit.

We used a zero-dimensional, steady-state model, based on thermal equilibrium analysis, to estimate power, torque, fuel consumption and emissions of internal combustion engines when they are fueled with different ethanol-gasoline blends. This model predicted minor reductions (<2%) in the maximum delivered power and torque, and in the CO and NOx emissions when they are fueled with E20 instead of gasoline. Although ethanol has a lower energy content than gasoline, power remained essentially unchanged thanks to a minor increase (<2%) in fuel consumption. Reductions in NOx emissions are due to reductions in the maximum temperature reached inside the combustion chamber caused by the lower energy content and the higher latent heat of vaporization of ethanol compared to that of gasoline. CO_2 and unburned hydrocarbon (HC) emissions increased with ethanol content in the fuel. A minor increase (<2%) was estimated in these two pollutant emissions when using E20.

These estimated reductions are less than the variations of the measurements obtained in engine test benches and vehicles on chassis dynamometers. Experimental tests showed statistically insignificant differences in power, torque, fuel consumption and emission of pollutants in engines and vehicles. The same conclusions were obtained during the tests conducted every 10,000 km of vehicle operation, indicating that the addition of ethanol to the fuel does not significantly affect mechanical, energy or environmental performance, at least for the first 100,000 km of operation.

We learned from measuring λ at different conditions of vehicle operation that when they operate at full load, which corresponds to the conditions of maximum emission of pollutants ($0.9 < \lambda < 0.95$) and maximum fuel consumption, the addition of ethanol to the fuel forces the engines to operate with greater λ than when they operate with gasoline, reducing the net emission of pollutants. This effect disappears at partial engine loads.

Thermal equilibrium analysis of the tailpipe conditions (~100 °C) showed that the estimated emissions of VOCs were negligible ($EI < 10^{-6}$ g/kWh) and that ethane, formaldehyde, ethylene and ethanol are the most relevant VOCs in terms of the amount of mass emitted. The use of ethanol in the gasoline reduced those emissions by between 20–40%, with toluene, benzene and 1,3-butadiene being the VOCs that experienced the largest reductions in mass emissions. These reductions imply an average reduction of 17% for $\lambda < 1$ in the ozone formation potential, calculated following the methodology of the maximum indexes of reactivity (MIR).

Complementarily, we estimated the effect of the fuel change on the environment through a life cycle analysis based on the Eco-indicator-99 methodology. We obtained relative reductions of 1.3%, 1.4% and 12.9% in damages to human health, the ecosystem and natural resources, respectively, when vehicles are fueled with E20 instead of gasoline.

Acknowledgments: This work was partially financed by ECOPETROL, Ministry of Mines and Energy of Colombia, COLCIENCIAS (the Colombian Administrative Department of Science, Technology and Innovation) and CONACYT (The Mexican Council for Science and Technology).

Author Contributions: Juan E. Tibaquirá leaded of the experimental work. José I. Huertas leaded data analysis, analytical analysis and wrote the last version of the manuscript. Sebastián Ospina and Luis F. Quirama conducted experimental work under the direction of Juan E. Tibaquirá. José E. Niño conducted data analysis, analytical analysis an wrote the first draft of the paper under the direction of José I. Huertas.

Conflicts of Interest: The authors declare no conflict of interest.

Symbols and Acronyms

x	Mass fraction	-
τ	Torque	N m
$\dot{m}_f$	Fuel mass flow	g/h
η_{th}	Engine thermal efficiency	%
η_m	Engine mechanical efficiency	%
r	Engine compression ratio	-
λ	Relative air/fuel ratio	-
Ed	Engine displacement	L
EI	Emission Index	g/kWh
P	Power	kW
Nc	Engine cylinders number	-
A/F	Air-fuel ratio	-
CO	Carbon monoxide	-
CO_2	Carbon dioxide	-
E20	Gasoline with 20% v/v content of ethanol	-
LHV	Fuel low heating value	kJ/kg
masl	Meters above the sea level	m
HC	Unburned hydrocarbons	-
MIR	Maximum index of reactivity	g O_3/gVOC
NEDC	New European driving cycle	-
NOx	Nitrogen oxides	-
OFP	Ozone formation potential	-
RPM	Engine rotating speed	Rev/min
RVP	The Reid Vapor Pressure	
SFC	Specific Fuel Consumption	g/kWh
HC	Total unburned hydrocarbons	-
VOC	Volatile organic compounds	-

References

1. U.S. Energy Information Administration. *Annual Energy Outlook 2017*; U.S. Energy Information Administration: Washington, DC, USA, 2017.
2. Costagliola, M.A.; de Simio, L.; Iannaccone, S.; Prati, M.V. Combustion efficiency and engine out emissions of a S. I. engine fueled with alcohol/gasoline blends. *Appl. Energy* **2013**, *111*, 1162–1171. [CrossRef]
3. Iodice, P.; Senatore, A.; Meccariello, G.; Prati, M.V. Methodology for the analysis of a 4-stroke moped emission behaviour. *SAE Int. J. Engines* **2009**, *2*, 617–626. [CrossRef]

4. Park, C.; Choi, Y.; Kim, C.; Oh, S.; Lim, G.; Moriyoshi, Y. Performance and exhaust emission characteristics of a spark ignition engine using ethanol and ethanol-reformed gas. *Fuel* **2010**, *89*, 2118–2125. [CrossRef]
5. Iodice, P.; Senatore, A. Influence of Ethanol-Gasoline Blended Fuels on Cold Start Emissions of a Four-Stroke Motorcycle. Methodology and Results. In Proceedings of the ICE 2013, 11th International Conference on Engines and Vehicles, Napoli, Italy, 15–19 September 2013.
6. Costagliola, M.A.; Prati, M.V.; Florio, S.; Scorletti, P.; Terna, D.; Iodice, P.; Buono, D.; Senatore, A. Performances and emissions of a 4-stroke motorcycle fuelled with ethanol/gasoline blends. *Fuel* **2016**, *183*, 470–477. [CrossRef]
7. Pulkrabek, W. *Engineering Fundamentals of the Internal Combustion Engine*; Prentice Hall: Passaic River, NJ, USA, 2004.
8. Al-Hasan, M. Effect of ethanol—Unleaded gasoline blends on engine performance and exhaust emission. *Energy Convers. Manag.* **2003**, *44*, 1547–1561. [CrossRef]
9. Doğan, B.; Erol, D.; Yaman, H.; Kodanli, E. The effect of ethanol-gasoline blends on performance and exhaust emissions of a spark ignition engine through exergy analysis. *Appl. Therm. Eng.* **2017**, *120*, 433–443. [CrossRef]
10. Naja, G.; Ghobadian, B.; Yusaf, T.; Mohammad, S.; Mamat, R. Optimization of performance and exhaust emission parameters of a SI (spark ignition) engine with gasoline e ethanol blended fuels using response surface methodology. *Energy* **2015**, *90*, 1815–1829.
11. Thangavel, V.; Yashwanth, S.; Bharadwaj, D. Experimental studies on simultaneous injection of ethanol e gasoline and n-butanol e gasoline in the intake port of a four stroke SI engine. *Renew. Energy* **2016**, *91*, 347–360. [CrossRef]
12. Elfasakhany, A. Investigations on the effects of ethanol–methanol–gasoline blends in a spark-ignition engine: Performance and emissions analysis. *Int. J. Eng. Sci. Technol.* **2015**, *18*, 713–719. [CrossRef]
13. Najafi, G.; Ghobadian, B.; Tavakoli, T.; Buttsworth, D.R.; Yusaf, T.F.; Faizollahnejad, M. Performance and exhaust emissions of a gasoline engine with ethanol blended gasoline fuels using artificial neural network. *Appl. Energy* **2009**, *86*, 630–639. [CrossRef]
14. Najafi, G.; Ghobadian, B.; Moosavian, A.; Yusaf, T.; Mamat, R.; Kettner, M.; Azmi, W.H. SVM and ANFIS for prediction of performance and exhaust emissions of a SI engine with gasoline-ethanol blended fuels. *Appl. Therm. Eng.* **2016**, *95*, 186–203. [CrossRef]
15. Schifter, I.; Diaz, L.; Rodriguez, R.; Gómez, J.P.; Gonzalez, U. Combustion and emissions behavior for ethanol-gasoline blends in a single cylinder engine. *Fuel* **2011**, *90*, 3586–3592. [CrossRef]
16. Hernandez, M.; Menchaca, L.; Mendoza, A. Fuel economy and emissions of light-duty vehicles fueled with ethanol e gasoline blends in a Mexican City. *Renew. Energy* **2014**, *72*, 236–242. [CrossRef]
17. Turner, D.; Xu, H.; Cracknell, R.F.; Natarajan, V.; Chen, X. Combustion performance of bio-ethanol at various blend ratios in a gasoline direct injection engine. *Fuel* **2011**, *90*, 1999–2006. [CrossRef]
18. Li, Y.; Gong, J.; Deng, Y.; Yuan, W.; Fu, J.; Zhang, B. Experimental comparative study on combustion, performance and emissions characteristics of methanol, ethanol and butanol in a spark ignition engine. *Appl. Therm. Eng.* **2017**, *115*, 53–63. [CrossRef]
19. Ozsezen, A.N.; Canakci, M. Performance and combustion characteristics of alcohol-gasoline blends at wide-open throttle. *Energy* **2011**, *36*, 2747–2752. [CrossRef]
20. Suarez-Bertoa, R.; Zardini, A.A.; Keuken, H.; Astorga, C. Impact of ethanol containing gasoline blends on emissions from a flex-fuel vehicle tested over the Worldwide Harmonized Light duty Test Cycle (WLTC). *Fuel* **2015**, *143*, 173–182. [CrossRef]
21. Carter, W.P.L. Development of Ozone Reactivity Scales for Volatile Organic Compounds. *Air Waste* **1994**, *44*, 881–899. [CrossRef]
22. Carter, W.P.L. Updated maximum incremental reactivity scale and hydrocarbon bin reactivities for regulatory applications. *Calif. Air Resour. Board Contract* **2009**, 07-339.
23. Goedkoop, M.; Spriensma, R. The eco-indicator 99: A damage oriented method for life cycle impact assessment. *Pain* **2001**, *11*, S95.