concawe

report no. 13/13

Assessment of the impact of ethanol content in gasoline on fuel consumption, including a literature review up to 2006

ISBN 978-2-87567-032-8

Assessment of the impact of ethanol content in gasoline on fuel consumption, including a literature review up to 2006

Prepared for the CONCAWE Fuels Quality and Emissions Management Group by its Special Task Force FE/STF-20:

R. Stradling (Chair)
A. Bellier
M.O. Del Rio Barrio
J.H. Farenback-Brateman
H. Hovius
A. Jackson
A. Joedicke
U. Kiiski
S. Maroto de Hoyos
W. Mirabella
C. Olivares Molina
K. Skaardalsmo
J. Williams

P.J. Zemroch (Consultant)
D.J. Rickeard (Consultant)

K.D. Rose (Science Executive)
N.D. Thompson (Technical Coordinator)

ABSTRACT

Ethanol, at low concentrations in motor gasoline, is known to impact both the fuel consumption and emissions from vehicles. Because ethanol has a lower energy content per litre compared to conventional hydrocarbon gasoline, a vehicle's volumetric fuel consumption generally increases when running on ethanol/gasoline blends. In principle, factors such as the higher octane number and high latent heat of vaporisation for ethanol could allow better engine efficiency which could mitigate this effect to some extent. The degree to which modern vehicles can compensate for the lower energy content of ethanol compared to conventional gasoline is not reliably known, however. This is an important question because it impacts the interpretation of Well-to-Wheels results for biofuel blends used in conventional vehicles. For this reason, an assessment of published literature up to 2006 was completed in order to evaluate the impact of ethanol content on fuel consumption.

The scope of this literature assessment was on the use of low-level ethanol/gasoline blends, specifically 5% (E5) and 10% (E10) v/v ethanol in gasoline. These blends are the most common ethanol levels in Europe today and have been formalised in the CEN EN 228 standard for motor gasoline. This literature review did not evaluate the impact of other oxygenate types that are also allowed in the EN 228 standard.

Although many publications were evaluated, the number of studies containing relevant data was limited primarily because the experimental variability in fuel consumption results was relatively large. From this analysis, the following conclusions could be made from the evaluated publications:

- There is a relatively high incidence of incorrectly derived fuel consumption data, usually resulting in an underestimate of the increase in fuel consumption from ethanol-containing gasolines.
- For some studies on gasoline blends containing up to E20, the increase in mass fuel consumption (FC) was typically only about 50% of the expected value, based on simply the loss in calorific value from ethanol addition. In the most extreme case, fuels with almost identical energy contents showed a fuel consumption difference of more than 4%, although for the majority of vehicles, the difference was generally less than 2%. For the largest data set (7 vehicles using up to 10 test fuels), the overall trend showed a 3.97% increase in fuel consumption with a 3.4% reduction in fuel energy content.
- It is not clear that this variation in FC results was related to variations in fuel parameters other than the ethanol content. Rather, it is assumed that the variability in FC was primarily a consequence of experimental variation and poorly controlled test procedures. The variability found in these published studies limits the firm conclusions that can be drawn about the influence of low levels of ethanol on vehicle fuel consumption.

These conclusions suggested that a more definitive vehicle study was warranted to determine whether modern vehicles can or cannot compensate for the lower energy content of ethanol-containing gasoline through better engine efficiency. Such a study has now been completed by the JEC[1] Consortium and is reported elsewhere [5].

1 Three organisations comprise the JEC Consortium: the Joint Research Centre (JRC) of the European Commission, the European Council for Automotive R&D (EUCAR), and CONCAWE

KEYWORDS

Ethanol, motor gasoline, petrol, fuel consumption, EN 228

INTERNET

This report is available as an Adobe pdf file on the CONCAWE website (www.concawe.org).

CONTENTS

Page

SUMMARY

Ethanol, at low concentrations in motor gasoline, is known to impact both the fuel consumption and emissions from vehicles. Because ethanol has a lower energy content per litre compared to conventional hydrocarbon gasoline, volumetric fuel consumption (FC) generally increases when running on ethanol/gasoline blends. In principle, factors such as the higher octane number and high latent heat of ethanol could allow better engine efficiency, which could also mitigate this effect to some extent. The degree to which modern vehicles can compensate for the lower energy content of ethanol is not reliably known, however. This is an important question because it impacts the interpretation of Well-to-Wheels results for biofuel blends and conventional vehicles. For this reason, an assessment of published literature up to 2006 was completed in order to evaluate the impact of ethanol content in gasoline on FC.

The scope of this assessment was on the use of low-level ethanol/gasoline blends, specifically 5% (E5) and 10% (E10) v/v ethanol in gasoline. These blends are the most common ethanol levels in Europe today and have been formalised in the CEN EN 228 standard for motor gasoline. This literature review did not evaluate the impact of other oxygenate types that are also allowed in the EN 228 standard.

A literature review, completed on references up to 2006[2], identified approximately 25 studies for more detailed analysis that were considered to be most relevant on the impact of ethanol in gasoline on vehicle FC. Although some studies included information on much higher ethanol concentrations, such as E85 and E95, vehicle modifications would be required at these ethanol contents and the impact of FC alone could be confounded by hardware changes. For this reason, this literature assessment is limited to low-level ethanol blends in motor gasoline.

Although many studies were evaluated, the final set of relevant data was very limited. It was also evident from the available data that the degree of variability in FC results was relatively large. Thus non-ethanol data sets were also examined to evaluate the variability in FC that can typically be expected from vehicle testing programmes.

From the analysis of the available literature data, the following conclusions could be made:

- There is a relatively high incidence of incorrectly derived FC data, usually resulting in an underestimate of the FC from ethanol-containing gasolines. In some cases, this was due to the use of an unadjusted carbon weight fraction in the carbon-balance equation. In other cases, the gasoline equation from the US Environmental Protection Agency (EPA) was used that attempts to correct for differences in fuel calorific value.
- For some studies on gasoline blends containing up to 20% v/v ethanol (E20), the measured increase in mass FC was typically only about 50% of the expected value, based on simply the loss in calorific value when a certain volume of ethanol was added. For example, with an E10 blend, a 2% mass FC increase was measured compared to the 4% mass FC that was expected.

[2] This literature review was completed several years ago in order to complement the development of specifications for low-level ethanol/gasoline blends that were in progress at the time.

- In the most extreme case, fuels with almost identical energy contents showed a fuel consumption difference of more than 4%, although for the majority of vehicles, the difference was generally less than 2%.
- For the largest data set (7 vehicles using up to 10 test fuels), the overall trend showed a 3.97% increase in fuel consumption with a 3.4% reduction in fuel energy content. However, the evaluation of individual vehicles with more limited fuel sets could lead to very different conclusions.
- It is not clear that this variation in FC results could be related to variations in fuel parameters other than the ethanol content. Rather, it is assumed at this point that the observed variability in FC was a consequence of experimental variation and poorly controlled test procedures.
- The variability found in these studies limits the conclusions that can be drawn about the impact of low levels of ethanol content on vehicle FC.

These conclusions suggested that a more definitive vehicle study was warranted to determine whether modern vehicles can or cannot compensate for the lower energy content of ethanol-containing gasoline through better engine efficiency. Such a study has now been completed by the JEC Consortium and is reported elsewhere [5].

1. INTRODUCTION

In 2005, CONCAWE's Gasoline Task Force (FE/STF-20) agreed to evaluate the effect of ethanol in gasoline on fuel consumption (FC) and regulated exhaust emissions. The primary focus of this evaluation was on FC, because this information was needed as an input to the JEC Consortium's work on the Well-to-Wheels (WTW) analysis of current and future fuels and powertrains [1].

This evaluation began by assessing literature published before 2006 covering these topics. A comprehensive literature search was completed from scientific databases and about 25 papers, considered to be the more relevant publications, were selected for more detailed assessment.

The scope of this assessment was on the use of low-level ethanol/gasoline blends, mostly 5% v/v (E5) and 10% v/v (E10) ethanol in gasoline. These blends were selected because they were considered at the time to be the most relevant blends for broad market gasoline use in Europe over the coming decade. Some papers included information on higher ethanol concentrations, including E85 (or E95 in one case) but, at these ethanol concentrations, flexi-fuel vehicle (FFV) modifications were required such that fuel effects could be confounded with hardware effects.

Even from this relatively small number of literature reports, the relevant data on FC effects was very limited and additional sources of data were sought. Useful data became available at about the same time from another JEC Consortium study on evaporative emissions [3], which evaluated vapour pressure changes due to ethanol. From this study, it was also evident that the variability in FC results was relatively large. For this reason, non-ethanol data sets were also examined to evaluate the variability in FC results that could not be due to ethanol effects.

This report describes the conclusions from published studies through to 2006 that were selected for further evaluation and summarises the overall effect of ethanol content on FC.

2. THEORETICAL EFFECTS

2.1. INTRODUCTION

The physical and chemical properties of ethanol differ substantially from those of refinery derived gasoline and give rise to several different ways in which the measured FC of a gasoline engine could be affected. The main influences of ethanol compared to fossil gasoline are:

- A lower energy content (Lower Heating Value (LHV)) of ethanol, requiring a greater mass of fuel to be combusted compared to gasoline in order to release an equivalent amount of energy.
- Higher density of ethanol, requiring a smaller volume of fuel for a given mass of fuel. This density effect is relatively small so the energy content per litre of ethanol is also lower than for conventional gasoline.
- Lower carbon weight fraction and a higher oxygen content in ethanol/gasoline blends, reducing the mass of air required to combust a given mass of fuel. These factors may change the effective mixture strength in the combustion chamber, and thus change the combustion efficiency of the engine.
- Higher octane value of ethanol may allow the engine to operate under more optimised ignition timing at higher engine loads (if these are encountered during the driving cycle), leading to higher combustion efficiency.
- The combination of heating value and stoichiometry also affects the airflow requirements at a given power output. This will impact the throttle setting which has a strong influence on the overall efficiency of the engine.
- The high latent heat of vaporisation of ethanol can potentially provide a high level of charge air cooling, increasing the air density and thus increasing the mass of fuel in the engine cylinder. This may also impact the throttle setting, as mentioned above.
- The volume of fuel in the cylinder depends on its mass and density. The mass of ethanol will be higher due to the lower LHV and the density (as a gas) will be lower due to ethanol's relatively low molecular weight (compared to gasoline). The greater the volume occupied by the fuel, the lower the volume available for air, and thus the need to reduce the throttling in order to maintain the air flow.
- Different volatility characteristics (and a higher latent heat of vaporisation) for ethanol/gasoline blends leading to changes in fuel-air mixing and combustion characteristics.
- Chemical kinetic effects of ethanol reaction products on the laminar flame speed and thus the combustion efficiency.

The objective of this literature review then was to assess the relative importance of these potential factors in conventional vehicles operating on low-level ethanol/gasoline blends.

2.2. TYPICAL PROPERTIES

Some typical properties for gasoline and ethanol are compared in **Table 1**, excluding volatility-related properties. The influence of ethanol content on volatility and vapour pressure are not trivial, however, and have been considered in detail elsewhere [2].

Table 1 Key physical properties of gasoline (Unleaded Gasoline 95RON) and ethanol

Parameter	Unleaded Gasoline (95RON)	Ethanol	% change from gasoline to ethanol	% change from ethanol to gasoline
Density (kg/litre)	0.745	0.794	6.6%	-6.2%
Research Octane Number (RON)	95	>100	==	==
Lower Heating Value (MJ/kg)	43.2	26.8	-38.0%	61.2%
Lower Heating Value (MJ/litre)	32.2	21.3	-33.9%	51.2%
Carbon weight fraction	0.864	0.522	==	==
Hydrogen weight fraction	0.136	0.130	==	==
Oxygen weight fraction	0.0	0.348	==	==
Stoichiometric Air-Fuel (A/F) ratio (AFR)	14.57	8.94	-38.6%	63.0%
Carbon emissions (gCO_2/MJ)	73.3	71.4	-2.6%	2.7%
Mean Molecular Weight	88.6	46.1	==	==
Latent Heat of vaporisation (MJ/kg)	306	855	==	==

Based on the properties in **Table 1**, it can be seen that going from a typical hydrocarbon-only gasoline to pure ethanol would require 61% higher mass fuel flow (or 51% higher volume fuel flow) to provide the same fuel energy content. Thus, if there were no change in the overall thermal efficiency of the engine due to the fuel change, this difference would substantially impact the fuel consumption (FC) of the vehicle.

Because fuel is purchased by the litre, the volumetric FC change is more relevant to consumers, although the handling of mass FC data removes one additional processing step. For example, based only on the lower energy content of ethanol compared to gasoline:

- For a 10% v/v ethanol/gasoline blend (commonly called ‘E10’), the volumetric FC should increase by 3.5% and the mass FC should increase by 4.2%.
- For a 5% v/v ethanol/gasoline blend (commonly called ‘E5’), the volumetric FC should increase by 1.7% and the mass FC should increase by 2.1%.

This apparent non-linearity in the % FC increase is because the energy content of the ethanol/gasoline blend is taken as the denominator for the calculation and becomes a smaller number as the ethanol fraction increases. The response is shown in **Figure 1** on a volumetric basis and in **Figure 2** on a mass basis.

Figure 1 Relative benefit in volumetric calorific value for hydrocarbon-only gasoline compared to ethanol/gasoline blends

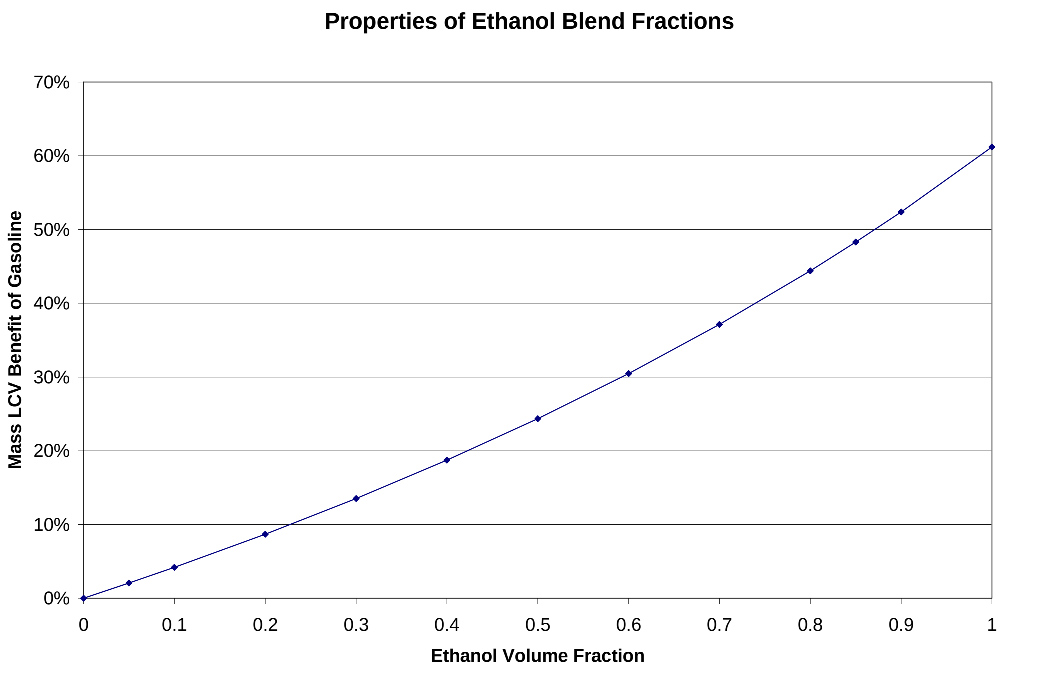
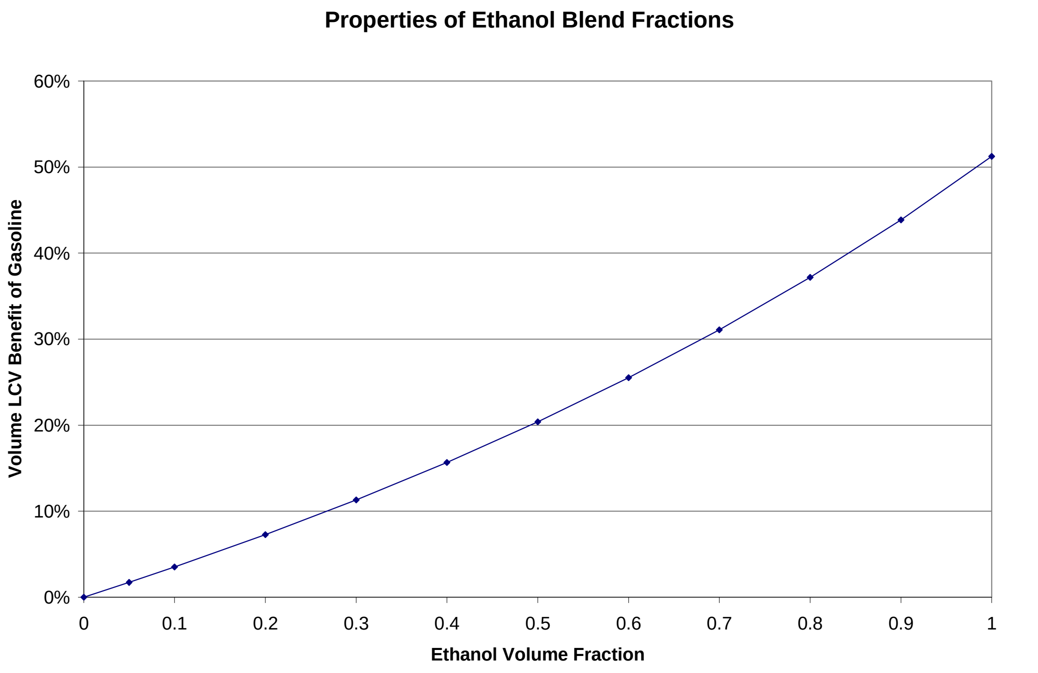
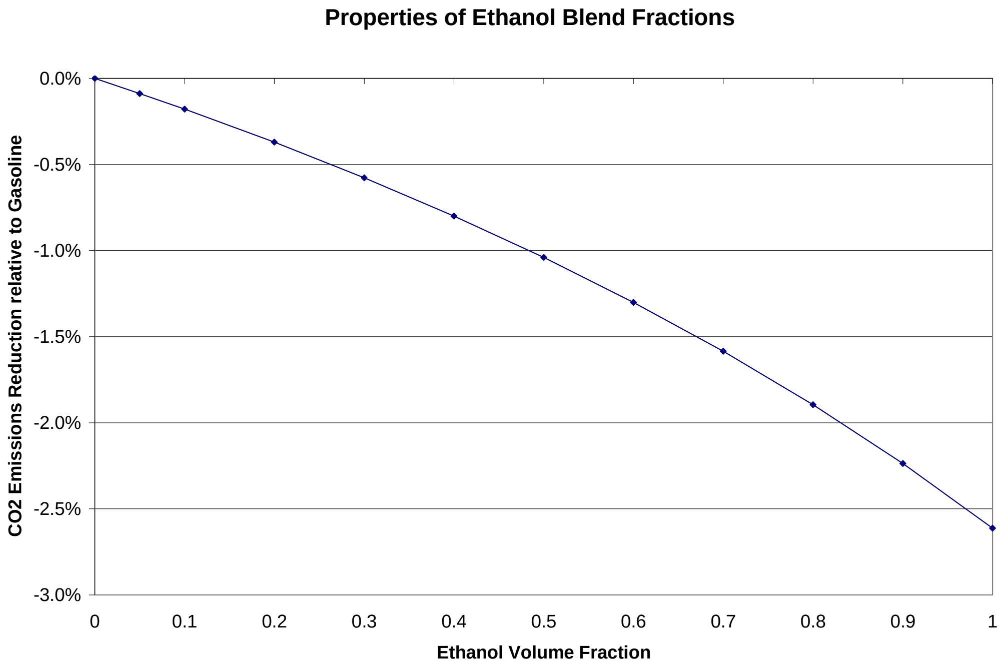


Figure 2 Relative benefit in mass calorific value for hydrocarbon-only gasoline compared to ethanol/gasoline blends



Although the FC is higher for ethanol/gasoline blends, the total carbon emissions per unit of energy (g/MJ basis) are slightly lower for ethanol. This is because the C/H ratio for ethanol is lower than that for conventional gasoline. The tailpipe carbon dioxide (CO_2) emissions are directly related to the total carbon emissions, except for a very small effect due to changes in carbon monoxide (CO) and hydrocarbon (HC) emissions. For 100% ethanol then, it is estimated that the CO_2 emissions will be 2.6% lower than for hydrocarbon-only gasoline, assuming that the same energy efficiency is maintained by the engine. For E10, the CO_2 emissions will be 0.18% lower, while for E5, the CO_2 emissions will be 0.09% lower, as shown in **Figure 3**.

Figure 3 Relative reduction in CO_2 emissions for ethanol blends compared to hydrocarbon-only gasoline



2.3. THEORETICAL EFFECTS OF LATENT HEAT AND THROTTLING

Properties of ethanol

Gasoline, ethanol and air have the following typical properties:

Table 2 Key properties of gasoline (Unleaded Gasoline 95RON), ethanol, and air

	Gasoline	**Ethanol**	**Air**
H_c lower heating value (MJ/kg)	43.2	26.8	
A/F stoichiometric air/fuel ratio (AFR)	14.57	8.94	
h_{vap} vaporization latent heat (kJ/kg)	306 (1)	855 (1)	
c_p specific heat at constant pressure (kJ/kg-K)	2.05 (2)	2.47	1.004
M molecular mass (g/mol)	88.6	46.1	28.97

(1) From Bromberg, Cohn and Heywood 2006 [6]
(2) Calculated for a typical gasoline

2.3.1. The effect of airflow and throttling

In stoichiometric Port Fuel Injected (PFI) and Direct Injection (DI) gasoline engines, engine power is controlled by the amount of fuel/air mixture that is allowed into the engine. By altering the position of the throttle valve, more or less air is allowed into the engine and the appropriate amount of fuel is injected downstream, either in the intake port or the cylinder. Since the throttle acts as a restriction to air flow, some energy is lost as the air passes through the throttle, and this loss is greatest when the throttle is at smaller opening positions, i.e. at lower engine loads.

Any change that increases the amount of intake gas needed to produce a given power will require a wider throttle opening to allow the higher volume through; this would directionally improve the efficiency of the engine. Such changes could, of course, affect engine operation in other ways as well, so this is just one factor to consider. As an example, the use of Exhaust Gas Recirculation (EGR) increases the mass of intake gas needed to deliver a given mass of fuel into the engine. For our present purpose, the presence of ethanol in the fuel will affect the air/fuel ratio for stoichiometry and the potential impact of this effect is discussed in this section.

By definition:

$$N = \eta \dot{m}_f H_c \tag{1}$$

Where:

- N is power (Watts)
- η is thermal efficiency
- $\dot{m}_f$ is mass flow of fuel (kg/s) and
- H_c is the Lower Heating Value of the fuel (J/kg).

Therefore:

$$\dot{m}_f = \frac{N}{\eta H_c} \tag{2}$$

For a stoichiometric engine, by definition:

$$\dot{m}_a = {}^{A}\!/\!_{F}\, \dot{m}_f \tag{3}$$

Where m_a is the mass flow of air and A/F is the stoichiometric air-fuel ratio (AFR).

Thus, for a given power N, the following values are obtained:

	Gasoline	Ethanol
$\dot{m}_f$ fuel mass flow (kg s^{-1})	$2.31\times10^{-5}\,\frac{N(kW)}{\eta_{gas}}$	$3.73\times10^{-5}\,\frac{N(kW)}{\eta_{EtOH}}$
$\dot{m}_a$ air mass flow (kg s^{-1})	$33.7\times10^{-5}\,\frac{N(kW)}{\eta_{gas}}$	$33.4\times10^{-5}\,\frac{N(kW)}{\eta_{EtOH}}$

With these properties of gasoline and ethanol, there is no significant difference in the air mass flow for both cases, assuming the thermal efficiency is unchanged.

Thus, with this small change in airflow, throttling should have no significant effect on cycle efficiency.

2.3.2. Effect of latent heat of vaporisation (1)

When using ethanol, the amount of fuel injected and the latent heat of vaporisation are greater. Thus, the final temperature at the end of the intake stroke should be lower. This, in turn, decreases the tendency for engine knock at the end of the compression stroke. Therefore, if the engine is able to adapt its ignition timing, the spark may be advanced for ethanol fuel compared to gasoline. This change may increase the mean effective pressure and, in turn, increase the engine efficiency.

In order to obtain a rough approximation of this effect, the temperature at the end of the intake stroke can be calculated. By definition, the amount of heat needed to evaporate the fuel is given by:

$$\dot{Q} = \dot{m}_f \; h_{vap} \tag{4}$$

Thus, for a given power output, *N*, the following values are obtained:

	Gasoline	Ethanol
$\dot{Q}$ Heat absorbed in vaporization (kJ/s)	$7.08 \times 10^{-3} \dfrac{N(kW)}{\eta_{gas}}$	$31.90 \times 10^{-3} \dfrac{N(kW)}{\eta_{EtOH}}$

This means that, for equal engine efficiencies, the amount of heat needed to evaporate ethanol is 350% greater than that required to evaporate gasoline.

Assuming that the heat is removed from the mixture of fuel and intake air at constant pressure, this heat equals:

$$\dot{Q} = \dot{m}_f \; c_{pf} \; \Delta T + \dot{m}_a \; c_{pa} \; \Delta T \tag{5}$$

Therefore:

$$\Delta T = \frac{\dot{Q}}{\dot{m}_f \; c_{pf} + \dot{m}_a \; c_{pa}} \tag{6}$$

Substituting the heat absorbed in the vaporization process:

$$\Delta T = \frac{\dot{m}_f \; h_{vap}}{\dot{m}_f \; c_{pf} + \dot{m}_a \; c_{pa}} \tag{7}$$

Finally:

$$\Delta T = \frac{h_{vap}}{c_{pf} + A/F \; c_{pa}} \tag{8}$$

Substituting numbers into this equation gives the following values:

	Gasoline	Ethanol
Temperature difference (ºC)	18.3	74.7

As was pointed out earlier, this latent heat effect for ethanol reduces the combustion temperature and the tendency of the engine to knock. Therefore, if the engine is able to adapt to the new fuel blend, it can also advance the spark timing in order to take advantage of this cooling effect.

2.3.3. The effect of latent heat (2)

In addition to increasing the efficiency of the engine in some cases (through adaptive spark timing), the extra charge cooling provided by ethanol evaporation, in theory, allows the engine to reach a higher peak power. The following paragraphs offer an explanation of this effect.

On one side, for equal efficiencies, the power of the engine is proportional to the product $\left(\dot{m}_f \times H_c\right)$. On the other side, for a given engine at a given intake pressure, the maximum amount of air/fuel mixture that can fit inside a cylinder is a consequence of the complete filling of the cylinder, that is, when the engine is charged with the maximum amount of mixture, it is not possible to push more inside.

To a first order approximation, this maximum is given by the final pressure reached at the end of the intake stroke. That is, when the pressure inside the cylinder equals the pressure inside the intake manifold (atmospheric pressure or turbocharger pressure), the air mass flow will stop.

If we assume that the mixture is an ideal gas, then:

$$pV = nRT = \frac{m}{M}RT = \left[\frac{m_a}{M_a} + \frac{m_f}{M_f}\right]RT \qquad (9)$$

Where:

- p is pressure
- V is volume
- n is the number of moles of gas (air + fuel)
- R is the universal gas constant
- T is the temperature
- m is the mass (m_a air or m_f fuel)
- M is molecular mass (M_a air or M_f fuel).

If the engine operates with a stoichiometric mixture, then:

$$pV = m_f\left[\frac{A/F}{M_a} + \frac{1}{M_f}\right]RT \qquad (10)$$

Thus, the mass of fuel charged inside the cylinder (m_f) is:

$$m_f = \frac{1}{\left[\frac{A/F}{M_a} + \frac{1}{M_f}\right]}\frac{pV}{RT} \qquad (11)$$

Where:

- p is pressure
- V is the volume of the cylinder and
- T is the temperature at the end of the intake stroke.

Up to this point, we have been working with mass flows. However, to apply the ideal gas equation, we also need the mass. This may be done using the following relationship:

$$m = \frac{\dot{m}}{\omega\, e} \tag{12}$$

Where:

- m is the mass charged inside one cylinder
- $\dot{m}$ is the mass flow entering the engine
- ω is the engine speed (in rev/second) and
- e is the number of admission strokes per revolution of the engine (for a four-stroke engine, this is the number of cylinders divided by two).

Substituting in the general equation:

$$\dot{m}_f = \frac{1}{\left[\frac{A/F}{M_a} + \frac{1}{M_f}\right]} \frac{pV\omega e}{RT} \tag{13}$$

And multiplying by $(\eta\, H_c)$, one obtains:

$$N = \frac{1}{\left[\frac{A/F}{M_a} + \frac{1}{M_f}\right]} \frac{pV\omega e}{RT} \eta\, H_c \tag{14}$$

Where the temperature, T, which appears in the equation represents the temperature at the end of the admission stroke.

If we call θ the temperature of the air in the intake manifold, then the temperature, T, at the end of the admission stroke, allowing for fuel evaporation, is given by:

	Gasoline	Ethanol
T temperature at the end of the admission stroke (in K)	Θ - 18.3	Θ - 74.7

Substituting values into this equation, we obtain:

For gasoline:

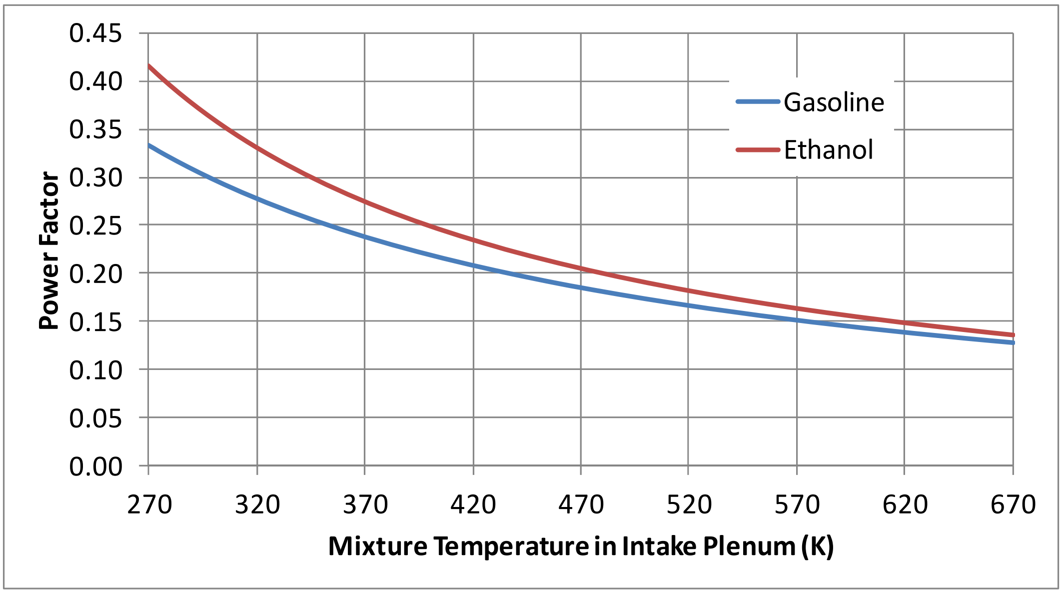
$$\frac{N}{\left(\frac{\eta_{gas}\, pV\omega e}{R}\right)} = 84.01\left(kJ\ mol^{-1}\right)\frac{1}{\left(\theta\left(K\right) - 18.3\right)} \tag{15}$$

And for ethanol:

$$\frac{N}{\left(\frac{\eta_{EtOH}\, pV\omega e}{R}\right)} = 81.14\left(kJ\ mol^{-1}\right)\frac{1}{\left(\theta\left(K\right)-74.7\right)} \qquad (16)$$

Assuming equal efficiencies for gasoline and ethanol, the power represented by the factor $\frac{N}{\left(\frac{\eta\, pV\omega e}{R}\right)}$ is then given in the following graph (**Figure 4**):

Figure 4 Power factors due to the charge cooling effect of ethanol compared to gasoline at different intake temperatures



As can be seen in this graph, the charge cooling effect achieved during the vaporization of the fuel increases the density of the mixture and allows extra charging of the cylinder. This is the case even though ethanol has a LHV approximately 39% lower than that of gasoline and requires 3.5% more mixture mass flow for a given power.

2.4. EPA FUEL CONSUMPTION CORRECTION

In light-duty emissions testing, the FC is normally calculated by the Carbon Balance method, using the measured carbon emissions during the test cycle. More details on this are given in **Appendix 2**. For gasoline vehicles, the EPA version of this equation contains an empirical energy correction formulation with an R-factor of 0.6. This effectively means that only 60% of any increase (or decrease) in calorific value is reflected in the change in fuel consumption. The background to the development of this empirical relationship does not appear to be referenced by the EPA FC equation, however the outcome is still of interest because it implies that vehicles on which this equation was based did not observe a 1:1 relationship between fuel energy content and fuel economy.

3. LITERATURE ASSESSMENT

A list of the 29 published studies up to 2006 that were assessed for this report is given in **Appendix 1**. One of these reports is the JEC study of ethanol effects on evaporative emissions [3] and is covered in more detail in **Appendix 3**. From the remaining 28 studies, reliable information on the effect of ethanol on fuel consumption was obtained from just 16 studies for the reasons described in **Appendix 1**.

3.1. INFORMATION ON FUEL CONSUMPTION

Appendix 1 summarises the findings of the studies that provided FC information on low-level ethanol/gasoline blends and shows which data were considered useful for further analysis.

Based on our assessment of these publications, there is not in general a clear picture of the effect of ethanol content on the measured FC. In many cases where more than one vehicle was tested, the results show significant vehicle-to-vehicle variation. For example, reference [A19] (see **Appendix 1**) shows that the change in volumetric fuel economy (which is the inverse of FC) from the use of E10 varied between a 12.4% increase and a 17.8% decrease. Efficiency changes of this magnitude between vehicles seems unlikely, even if stoichiometry, octane and volatility effects were combined in some manner. Based on the analysis in **Section 2** we would expect a 5% decrease in volumetric fuel economy. For this reason, the large variation in results suggests that there were problems with the experimental procedure or measurements.

In other studies, the comparison between different fuels does not appear to be on a fair basis. For example, in reference [A15], the gear ratios of an E85 flexi-fuel vehicle were changed to reduce the engine speed by about 10%. In reference [A21], results obtained on different fuels were compared between a conventional vehicle having a single port injected (SPI) engine and a modified vehicle using multiport injection (MPI) and an improved engine control system running on E95. However, the effect of these high ethanol concentrations in dedicated vehicles is not the main interest of this study.

3.2. FINAL FUEL CONSUMPTION DATA

From the published literature evaluated in **Section 3.1**, only a small number of studies provided reliable FC data and some of these required recalculation due to inconsistencies between the regulated emissions and the calculated FC data. The resulting data are summarised in **Table 3** in terms of the measured increase in mass FC. Also included in this table is the associated decrease in mass Lower Calorific Value (LCV)[1].

In about half of the studies, the mass calorific value is provided, although in one case the data are unrealistic (reference [A21]). The final column gives an estimated LCV decrease for the particular fuel blend, which is based on the typical gasoline and ethanol data given in **Section 2**, **Table 1**. This is used as a simple check on the LCV data provided in the literature studies.

[1] Lower Calorific Value (LCV) is an alternative name for the Lower Heating Value (LHV)

Table 3 Fuel consumption data from published literature studies

Reference (App 1)	**Description**	**Fuel Blend**	**Average reported mass FC increase**	**Mass LCV decrease reported in the study**	**Mass LCV decrease estimated from Section 2.0**
A5	Newer vehicles	E20	+ 4.8%	- 8.05%	- 8.0%
A5	Older vehicles	E20	+ 3.5%	- 8.05%	- 8.0%
A14	Full load conditions	E85	+ 29%	- 27.2%	- 32.6%
A14	Steady state road conditions	E85	+ 32%	- 27.2%	- 32.6%
A14	FTP and highway tests	E85	+ 46%	- 27.2%	- 32.6%
A21	16,000 km of on-road driving	E95	+ 37.7%	The reported data gave - 41.6%, but the gasoline value was incorrect	- 36.2%
A25	NEDC	E5	+ 0.99%	Result not reported	- 2.0%
A26	Hot start (real world) cycles	E10	+ 1.24%	Result not reported	- 4.0%
A27	NEDC	E5	+ 0.18%	Result not reported	- 2.0%
A27	NEDC	E10	+ 2.19%	Result not reported	- 4.0%
A28	FTP	E10	+ 3.7%	- 4.4%	- 4.0%

The measured mass FC increase data from **Table 3** have been plotted against the expected mass FC increase, and the results are shown in **Figure 5**. The expected mass FC increase is derived from the reduction in mass LCV, assuming no change in the thermal efficiency of the engine. Except for the results from reference [A21], the published mass LCV data have been used. For this reference, and all cases where LCV data were not reported, the simple estimated value is used.

Figure 5 shows all of the data from **Table 3**, including some E85 and E95 blends giving high percentage changes in FC. The plot also includes a trend line (linear) and lines with gradients of 1.0 and 0.5. The gradient of the trend line is 0.84, indicating that 84% of the estimated increase in mass FC is typically measured in the vehicle tests. Since the gradient of the trend line is highly influenced by the fuels with high ethanol blend concentrations, the analysis has also been performed with these data points excluded, as shown in **Figure 6**.

Figure 6 also includes a trend line and other lines with gradients of 1.0 and 0.5. The gradient of the trend line is 0.52, indicating that only about half of the estimated increase in mass FC is typically measured in the vehicle tests. There is no evidence that the data at the E5, E10 and E20 levels differ significantly from the overall trend, since the trend line essentially goes through the origin.

Figure 5 Comparison of measured and expected mass FC increases for all data reported in **Table 3**.

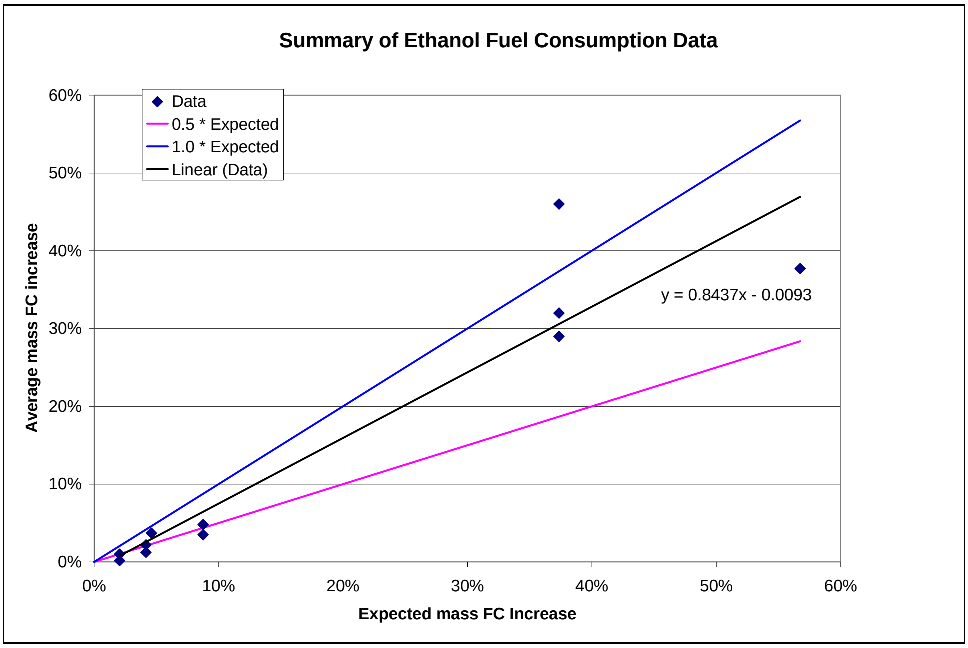
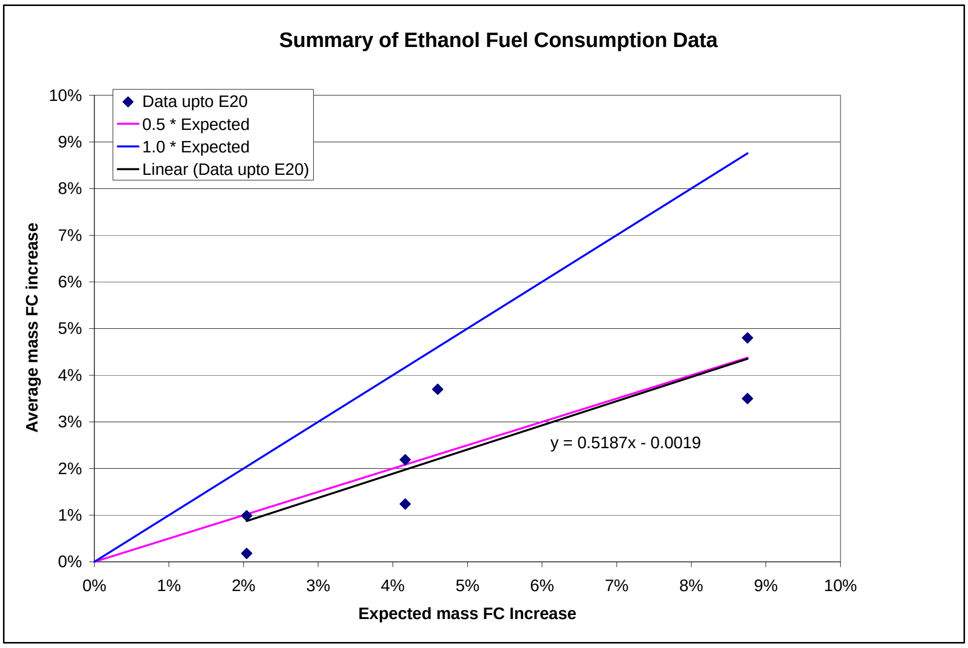


Figure 6 Comparison of measured and expected mass FC increases for fuels containing no more than 20% ethanol, data reported in **Table 3**



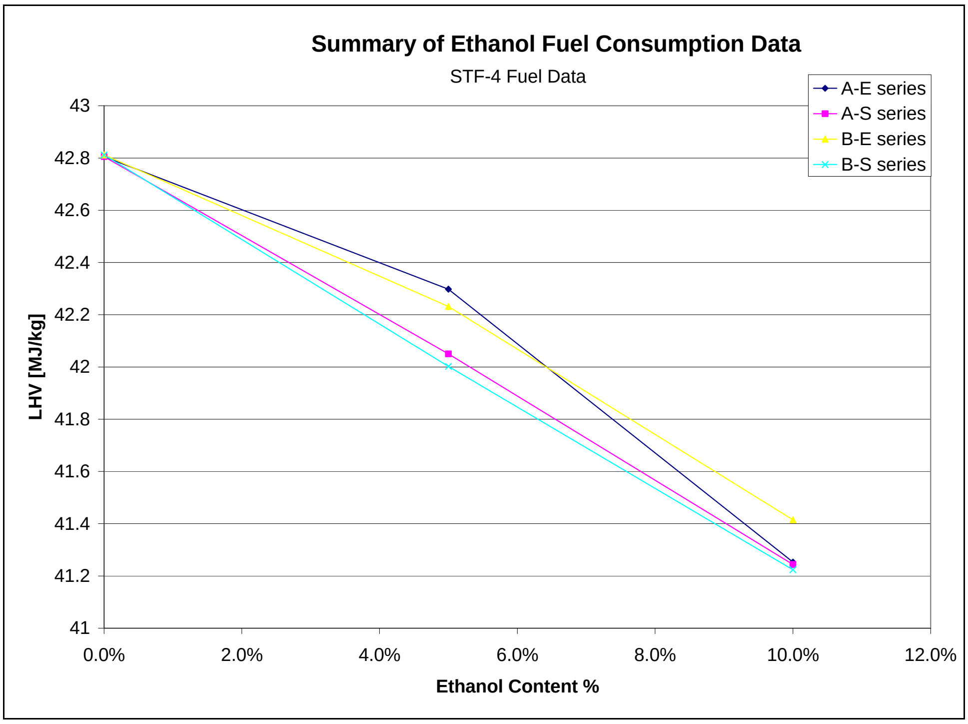
4. CONCAWE DATA

4.1. JEC EVAPORATIVE EMISSIONS PROGRAMME

While this literature review was in progress, the JEC Consortium also completed an evaporative emissions study on ethanol/gasoline blends [3] and the results from this study were relevant to this report's FC question.

In [3], ten test fuels were prepared using two base gasolines (A and B) having different Reid Vapour Pressures (RVP). Using each base fuel, E5 and E10 fuels were made as splash blends (S series) and as matched RVP blends (E series). A total of seven vehicles were tested in this study, although not all vehicle and fuel combinations were run. The variation in fuel calorific value with ethanol content is shown in **Figure 7**.

Figure 7 Variation in fuel calorific value (LHV) with ethanol content for ten test fuels [3]



The matrix of vehicle and fuel combinations that were run is shown in **Table 4**. In the first two vehicles, all ten fuels were tested, while only five of the fuels were tested in the second vehicle (the BMW).

Table 4 Vehicles and fuel from reference [3]

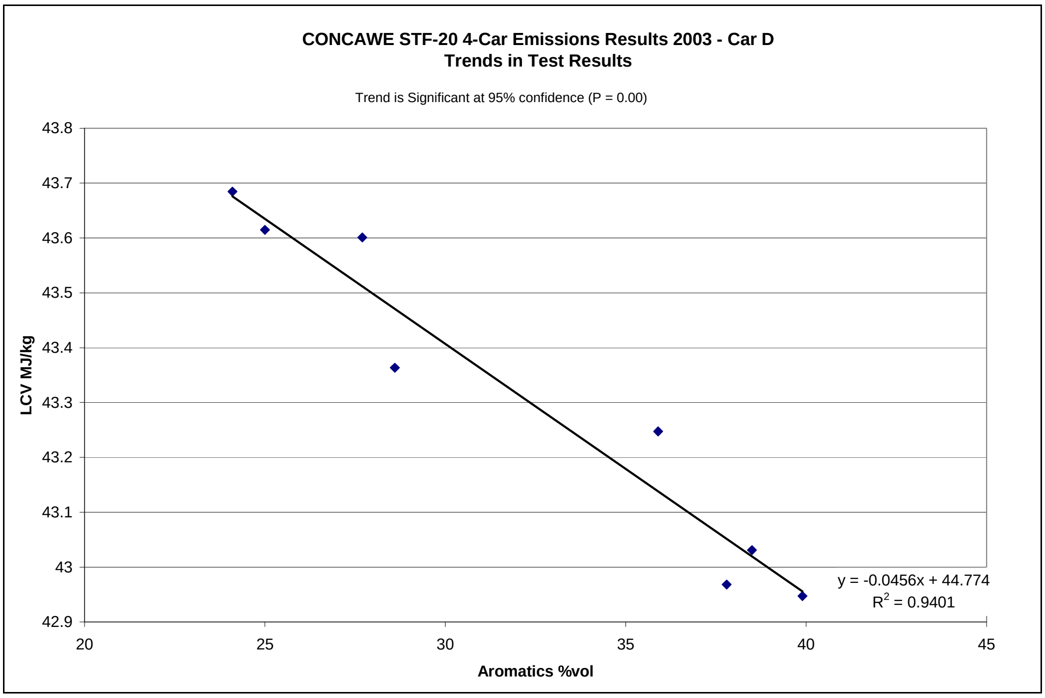
Vehicles	A	A5E	A10E	A5S	A10S	B	B5E	B10E	B5S	B10S
Ford Focus	x	x	x	x	x	x	x	x	x	x
VW Polo	x	x	x	x	x	x	x	x	x	x
Renault Megane	x	x		x		x	x	x	x	x
Toyota Corolla	x	x		x	x	x			x	x
Lancia Y10	x			x	x	x			x	x
VW Golf	x	x		x		x	x		x	
BMW 7 Series	x			x		x			x	x

The fuel consumption results for these seven vehicles are shown in **Appendix 3.1**. For the seven vehicles taken together, the increase in FC (3.97%) is close to that expected from the 3.4% reduction in fuel energy content for the E10 blends. For individual vehicles, a relatively high level of unexplained variation (noise) is evident, that is, fuels with relatively similar calorific values can have FC values that varied by 2% to 3%. Thus, with a limited data set (one vehicle and two fuels), the measured trends could be much more extreme than those seen on this fleet study.

4.2. CONCAWE GASOLINE EMISSIONS PROGRAMME

A set of eight test fuels was blended to investigate variations in aromatics, olefins, volatility and Final Boiling Point (FBP) [4]. The variation in calorific value was due to these other property changes, mainly from the variation in aromatics content. The maximum LCV was 43.68 MJ/kg from a 24% aromatic fuel, while the minimum LCV was 42.95 MJ/kg from a 40% aromatics fuel. The relationship between aromatics and LCV is shown in **Figure 8**. This 1.7% difference in LCV is slightly less than that seen from an E5 splash blend and less than half the variation seen in the evaporative emissions study (described in **Section 4.1**). Four vehicles were tested on these eight test fuels.

Figure 8 Variation in LCV with aromatic content for the eight test fuels [4]



The FC results for these four vehicles are presented in **Appendix 3.2**. Although two of the vehicles (Cars B and D) showed a trend toward increasing FC with lower fuel energy content that was close to a constant energy relationship, the other two vehicles gave very poor correlations between these two parameters. For these two vehicles, the measured FC on different fuels having the same energy content varied by more than 4% (Car C). However, in the majority of cases, the FC varied by +/-1% for fuels having the same energy content.

Because all fuels were tested on all vehicles, the results could be combined to give a mean result. For all eight test fuels, the mean result showed a 0.8% increase in FC for a 1.7% reduction in fuel energy content, however this trend was not significant at the 95% confidence level.

5. CONCLUSIONS

Theoretically, there are a number of primary and secondary mechanisms through which the blending of ethanol in gasoline can affect the FC of a vehicle over mixed driving conditions.

- Lower heating value of ethanol requires a greater mass of fuel to release a given quantity of energy. With an E10 gasoline compared to hydrocarbon-only gasoline, this effect is estimated to increase the FC by 4.2%.

- Higher density of ethanol requires a smaller volume of fuel for a given mass. This effect applies only to volumetric FC and is estimated to decrease the volumetric FC by -0.7% for an E10 gasoline compared to hydrocarbon-only gasoline.

- The lower carbon weight fraction and higher oxygen content in ethanol reduces the mass of air required to combust a given mass of fuel. This may change the effective mixture strength in the combustion chamber, and thus change the combustion efficiency of the engine.

- The combination of heating value and stoichiometry will affect the airflow requirements at a given engine power output. This will impact the throttle setting, which has a strong influence on the overall efficiency of the engine.

- The volume of fuel in the cylinder depends on the fuel's mass and density. For ethanol, the mass will be higher due to the low heating value and the density (as a gas) will be lower due to ethanol's relatively low molecular weight compared to gasoline. In the combustion chamber, the greater the volume occupied by fuel, the lower the volume available for air, and thus the need to reduce throttling in order to maintain the air flow.

- The higher octane value of ethanol may allow the engine to operate under more optimised ignition timing regimes at higher loads (if these are encountered during the test cycle), leading to higher combustion efficiency. The engine could potentially be adapted to take advantage of this effect.

- The very high latent heat of vaporisation of ethanol can potentially provide a high level of charge air cooling, increasing the air density and thus the mass of fuel in the cylinder. This may also impact the throttle setting, as mentioned above.

- Different volatility characteristics for ethanol and a higher heat of vaporisation could result in changes to fuel-air mixing and combustion characteristics. The magnitude of this effect on FC was not estimated in this report.

- Ethanol could also introduce chemical kinetic effects on the laminar flame speed and thus the combustion efficiency. The magnitude of this effect on FC was not estimated in this report.

Our review of the published literature through 2006 resulted in the following conclusions:

- There was a relatively high incidence of incorrectly derived FC data, usually resulting in an underestimate of the FC for ethanol-containing fuels. In some cases this was due to the use of an unadjusted carbon weight fraction in the carbon-balance equation. In other cases, the EPA gasoline equation was used which attempts to correct for differences in fuel calorific value.
- For tests with fuel blends up to E20, the typical increase in mass FC was about 50% of the expected value, based simply on the decrease in calorific value with ethanol addition. For example, for an E10 blend, a 2% mass FC increase was measured compared to the 4% expected from the decrease in calorific value when ethanol was added.
- From the information provided above, it is estimated that approximately 50% of the increase in mass FC is compensated by the listed mechanisms.

From the analysis of the two CONCAWE vehicle and fuel studies [3,4], the following conclusions can be made:

- In the most extreme case, fuels with almost identical energy content showed a FC difference of more than 4%, although for the majority of vehicles the difference was generally less than 2%.
- This variation in FC did not appear to be related to fuel parameters other than the ethanol content. However, if it were due to other parameters, the effects are vehicle specific. Based on the results, it is assumed that the variation in results are most likely due to measurement variability (noise).
- This level of variability affects the conclusions that can be drawn on the impact of low levels of ethanol in gasoline on FC unless the experimental study is specially designed to answer the FC question. Consumers are unlikely to see small FC effects in real world driving but the quantitative impact of ethanol on FC is important on a fuel demand and CO_2 emissions perspective.
- For the largest data set (7 vehicles using up to 10 test fuels), the overall trend showed a 3.97% increase in FC with a 3.4% reduction in fuel energy content. However, the evaluation of individual vehicles with more limited fuel sets could lead to very different conclusions.

These conclusions suggested that a more definitive vehicle study was warranted to determine whether modern vehicles can compensate for the lower energy content of ethanol-containing gasolines through better engine efficiency. Such a study has been completed by the JEC Consortium and will be reported separately [5].

6. GLOSSARY

A/F	Air / Fuel
AFR	Air / Fuel Ratio
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CR	Compression Ratio
CWF	Carbon Weight Fraction
DVPE	Dry Vapour Pressure Equivalent
E5 / E10 / E20	2.7 / 3.7 / 7.4 wt% oxygen in gasoline, which is equivalent to 5 / 10 / 20% v/v ethanol in gasoline
E85	85% v/v ethanol in gasoline
EGR	Exhaust Gas Recirculation
EN 228	European standard for automotive gasoline
EPA	Environmental Protection Agency (USA)
EUCAR	European Council for Automotive R&D
FBP	Final Boiling Point
FC	Fuel consumption
FFV	Flexi-Fuel Vehicle
FTP	Federal Test Procedure
HC	Hydrocarbon
JEC	JRC/EUCAR/CONCAWE
JRC	Joint Research Centre (of the European Commission)
LCV	Lower Calorific Value (same as LHV)
LHV	Lower Heating Value (same as LCV)
MJ	Megajoule
MPGE	Miles Per Gallon Equivalent
MPI	Multi Port Injection
NEDC	New European Driving Cycle
RON	Research Octane Number
rpm	revolutions per minute
RVP	Reid Vapour Pressure
SPI	Single Port Injection
WOT	Wide Open Throttle
WTW	Well-to-Wheels

7. ACKNOWLEDGMENTS

This literature assessment was initiated by Neville Thompson who was CONCAWE’s Technical Coordinator for Fuels and Emissions before his untimely death in 2006. Through his co-authorship of this report, it is our privilege to recognise once again his important contributions to CONCAWE’s work in the area of fuels and vehicle emissions.

8. REFERENCES

1. JEC (2011) Well-to-wheels analysis of future automotive fuels and powertrains in the European context. Well-to-wheels report, version 3c. Report EUR 24952 EN-2011. Brussels: JRC, EUCAR, CONCAWE

2. EU (2009) Ethanol/petrol blends: volatility characterisation in the range 5-25 vol% ethanol (BEP525). TREN/D2/454-2008-SI.2.522.698, Final report. Brussels: EU Commission

3. JEC (2007) Effects of gasoline vapour pressure and ethanol content on evaporative emissions from modern cars. Report EUR 22713 EN. Brussels: JRC, EUCAR, CONCAWE

4. CONCAWE (2004) Fuel effects on emissions from modern gasoline vehicles. Part 2 – aromatics, olefins, and volatility effects. Report No. 2/04. Brussels: CONCAWE

5. JEC (2013) Effect of oxygenates in gasoline on fuel consumption and emissions in three Euro 4 passenger cars. Report EUR 26381 EN. Brussels: JRC, EUCAR, CONCAWE

6. Bromberg, L. et al (2006) Calculations of knock suppression in highly turbocharged gasoline/ethanol engines using direct ethanol injection. Cambridge MA: Massachusetts Institute of Technology

APPENDIX 1 RELEVANT PUBLICATIONS ON FUEL CONSUMPTION THROUGH 2006

Ref	Document	Year	Title	Author(s)	Information on Fuel Consumption	Key Conclusions
A1	SAE 2004-01-2003	2004	The effect of heavy olefins and ethanol on gasoline emissions	J. Pentikainen, L. Rantanen, and P. Aakko	Ethanol vs ethers increased the fuel consumption but the oxygen content was higher in the ethanol fuels than in the ether fuels (3.5% vs 2%). No ethanol vs base fuel data.	No useable data.
A2	Transport-2004, Vol XIX, No.1, 24-27	2004	The research into the influence of ecological petrol additives in the automobile laboratory	A. Butkus and S. Pukalskas	One carburetted vehicle showed higher FC on pure petrol (no ethanol) while the conventional vehicle showed no significant response to fuel composition. Data only shown in graphs so not easily extracted.	No useable data.
A3	Advances in Air Pollution (2003), 13(Air Pollution XI), 551-560	2003	Tests on a small four-stroke engine using gasoline-bioethanol mixtures as fuel	C. Arapatsakos, A. Karkanis, A., and P. Sparis	Small engine running an electrical generator with limited speed and mixture control. In particular, changes in mixture with ethanol content and lack of data on ethanol quality reduced the value of the data.	No useable data.
A4	Journal of Engineering for Gas Turbines and Power (2003), 125(1), 344-350	2003	The effect of adding oxygenated compounds to gasoline on automotive exhaust emissions	S.G. Poulopoulos and C.J. Philippopoulos, C.J.	Pollutant emissions and HC speciation data, but no CO_2 to allow FC calculation.	No useable data.
A5	University of Leeds course on SI engine emissions, Nov 2003, Vol. 2	2003	Alcohol fuel blends for SI engines	D. Worth	E20 effects on fuel consumption. 5 newer vehicles: FC increase ranged from 2.5% to 7.0%, depending on cycle and vehicle. Average approx 5%. "Less than expected, due to calibration and adaptation strategies." 4 older vehicles: Minor increase in fuel consumption, ranging from 0% to 6%, mainly vehicle dependent. Average looks to be about 3.5%.	Different cycles did not rank the same with different vehicles. By averaging the three cycles, the range of FC increase become less variable: 5 newer vehicles: 5.1, 3.8, 3.7, 5.5 and 5.9%, gave an average 4.8% FC increase 4 older vehicles: 5.6, 1.3, 2.2 and 5.0%, gave an average 3.5% FC increase.
A6	Atmos. Env., 36 (2002), 3495-3503	2002	Applicability of gasoline containing ethanol as Thailand's alternative fuel to curb toxic VOC pollutants from automobile emission	S.T. Leong, S. Muttamara, and P. Laortanakul	Strong focus on VOC emissions. No FC data.	No useable data.

Ref	Document	Year	Title	Author(s)	Information on Fuel Consumption	Key Conclusions
A7	Atmos. Env., 36, 403-410 (2002)	2002	Engine performance and pollutant emission of an SI engine using ethanol-gasoline blended fuels	W-D. Hsieh, R-H. Chen, T-L. Wu, and T-H. Lin	Graphs (Fig 3) too small to evaluate fully but the authors conclude in the text that mass fuel consumption (g/kJ) - where kJ are measured on dynamometer - are the same for all fuels. This implies that the ~10% less energy per g in the E30 fuel does not have any effect on the fuel consumption. Fuel flow measurement is not discussed, so it is assumed that the carbon balance method is used. The CWF of all fuels is practically constant at about 0.866 – according to the fuel property table - even though it should be about 0.76 for E30.	Due to the apparent CWF error, it is therefore possible that the fuel consumption is underestimated for the oxygenated blends. If this is the case, their data may show that the carbon emissions per kJ are constant, which is more reasonable. **Data have not been used.**
A8	Proceedings of the Air & Waste Management Association's Annual Conference & Exhibition, 94th, Orlando, FL, United States, June 24-28, 2001 (2001), 398-415	2001	A comparison of oxygenated and non-oxygenated gasoline use in the Denver area under wintertime low ambient temperature conditions	K.B. Livo, K. Nelson, R. Ragazzi, and S. Sargent	Overall, for all 24 cars a measured 1.4% to 0.7% decrease in fuel economy was registered. Tier 0 vehicles demonstrated a slightly larger increase in fuel economy loss than Tier 1 vehicles	No useable data.
A9	Env. Sci. & Tech., 35 (10), 1893 (2001)	2001	Environmental implications on the oxygenation of gasoline with ethanol in the metropolitan area of Mexico City	I. Schifter, M. Vera, L. Diaz, E. Guzman, F. Ramos, and E. Lopez-Salinas	Exhaust regulated (CO, NOx, and hydrocarbons) and toxic (benzene, formaldehyde, acetaldehyde, and 1,3-butadiene) emissions were evaluated for MTBE (5 vol %)- and ethanol (3, 6, and 10 vol %)-gasoline blends. No FC data.	No useable data.
A10	7th Intl. Conf. on Env., Sci., and Tech. (Sept. 2001)	2001	Comparison between methyl tertiary butyl ether and ethanol as oxygenate additives: the influence on the exhaust emissions	S.G. Poulopoulos and C.J. Philippopoulos	CO, HC and speciated HC results only.	No useable data.
A11	SAE 2001-01-1206	2001	Influence of ethanol content in gasoline on speciated emissions from a direct injection stratified charge SI engine	H. Sandquist, M. Karlsson, and I. Denbratt	Engine-out and tail-pipe emissions but no FC data.	No useable data

Ref	Document	Year	Title	Author(s)	Information on Fuel Consumption	Key Conclusions
A12	SAE 2001-28-0029	2001	A single cylinder engine study of power, fuel consumption, and exhaust emissions with ethanol	S. Maji, M.K. Gajendra Babu, and N. Gupta	Authors state an 8-10% lower energy consumption for E85 at WOT and 1800rpm. Simple estimates from graphs are lower, and very dependent on which conditions are selected. Relative benefit of E15 and E85 also quite variable. Engine is unrepresentative – 250 cc single-cylinder with maximum speed of 2200 rpm at CR of 7:1.	Unrepresentative engine giving variable benefits. Data were not used in evaluation.
A13	SAE 2000-01-1965	2000	Alcohol as automotive fuel - Brazilian experience	F.G. Kremer and A. Fachetti	Comparison is established between diesel fuel and a mixture of diesel + 3%ethanol. No difference but a decrease in max power was observed when using ethanol.	There are no numerical data and the text states that a 5% FC reduction is achieved with the mixture of diesel + 3% ethanol at full load. However, the power reached at full load with the mixture is lower and the fuel consumption cannot be directly compared. In terms of specific FC (i.e. litres per kilowatt), the text states that there is no significant difference.
A14	SAE 1999-01-3517	1999	Practical considerations for an E85-fueled vehicle conversion	R.B. Wicker, P.A. Hutchison, O.A. Acosta, and R.D. Matthews	Authors quote "corrected BSFC", but give no indication of why the correction has been applied or whether it is actually applicable to these fuels or tests. Although larger fuel injectors were fitted for E85, they did not fully compensate, and lambda was close to 1 for E85 but more typically 0.9 for gasoline. Across the speed range at full load, this fuel consumption (lb/bhp-h) is on average 29% higher for E85. Because of the higher density of E85, the volumetric fuel economy (miles per gallon) is about 24% lower with E85. Under two steady state road conditions, there was also a 24% mpg penalty, while FTP city and highway tests gave 32% and 31% mpg penalties.	Using E85 the following results are shown: 29% increase in FC across full load conditions, but not running as rich as gasoline. Under steady state road conditions, the 24% FE penalty corresponds to a 32% FC increase. Under FTP and Highway test, the 32% and 31% FE penalties correspond to 47% and 45% FC increases.

Ref	Document	Year	Title	Author(s)	Information on Fuel Consumption	Key Conclusions
A15	SAE 1999-01-3568	1999	Improving the fuel efficiency of light-duty ethanol vehicles--An engine dynamometer study of dedicated engine strategies	D.P. Gardiner, R.W. Mallory, Robert W. (Nexum Research Corporation); Pucher, Greg R. (Nexum Research Corporation); Todesco, Marc K. (Nexum Research Corporation); Bardon, Michael F. (Royal Military College of Canada); Markel, Tony J	If the driveline gearing of a dedicated E85 vehicle was changed to reduce the engine speed by about 10% it would be possible for a dedicated E85 engine to achieve fuel economy improvements of about 15% (MPGE basis) over a comparable gasoline engine. Reducing the speed of the dedicated E85 engine will provide greater relative improvements in fuel economy under operating conditions typically occurring during urban driving (i.e., lower average power) than those which occur during highway driving.	No useable data
A16	KFB-Meddelande Publication 1999:4	1999	Moderate additions of alcohols to gasoline. Laaginblandning av alkoholer i bensin.	A. Laveskog and K-E. Egebaeck	Old vehicles and not relevant test cycle.	No useable data
A17	SAE 1999-01-3570	1999	Effect of gasoline compositions and properties on tailpipe emissions of currently existing vehicles in Thailand	T. Thummadetsak, A. Wuttimongkolchai, S. Tunyapisetsak, and T. Kimura	THC, CO, NOx and air toxic emissions, but no FC data.	No useable data
A18	SAE 982531	1998	Final results from the State of Ohio ethanol-fuelled, light-duty fleet deployment project	K. Chandler, M. Whalen, and J. Westhoven	Old FFV vehicle using E85 (+33% FC reported)	No useable data
A19	J. Air & Waste Mgmt. Assoc., 48, 646 (1998)	1998	The effect of ethanol fuel on the emissions of vehicles over a wide range of temperatures	K.T. Knapp, F.D. Stump, and S.B. Tejada	Fuel Economy: Highly variable (vehicle to vehicle). Volumetric fuel economy (miles/gal) ranged from 12.4% increase (better) to 17.8% decrease (worse). Average value was close to zero.	**Data too variable to be used reliably.**

Ref	Document	Year	Title	Author(s)	Information on Fuel Consumption	Key Conclusions
A20	SAE 960855	1996	Comprehensive laboratory fuel economy testing with RFG and conventional fuels	T.A. Kellner, K. Neusen, D. Bresenham, M. Pike, and D. Rose	The average fleet fuel economy reduction generally mirrored the expected fuel economy reduction. The transient based IM240 tests did not exhibit the expected fuel economy reductions based on energy content reduction. The distribution of the tested vehicle/fuel matrix showed that a portion of the test vehicles experienced excessive fuel economy reduction and increases. No one control system exhibited the greatest fuel economy deviation (reduction and increases). No RFG consistently caused excessive fuel economy reduction or gains.	No useable data
A21	SAE 952749	1995	A comparative analysis of ethanol versus gasoline as a fuel in production four-stroke cycle automotive engines	B. Jones, K. Ready, R. Bach, D. Hansen, E. Kaitala, J. Larson, J. Morales, and C. Reese	Engine hardware changes included CR increase and ignition timing optimisation. 20.0 km/litre on gasoline and 14.52 km/litre on E95. Their LCV values (in MJ/kg) are incorrect, and in Btu/lb are reasonable for E95, but for gasoline it is too high. Using their fuel LCV data, they calculate better energy efficiency for the E95 vehicle, however by recalculating (from estimated LCV and densities) some of this benefit disappears.	FC is 37.7% greater from E95 fuel. From a recalculated energy basis, we would expect it to be 45.4% higher.
A22	EMPA Report 202,672 (Sept. 2002)	2002	Bio-ethanol Projekt - Potential der bio-ethanol beimischung im benzin und diesel-treibstoff untersuchungen hinsichtlich des emissionsverhaltens an einem nutzfahrzeug motor und zwei personenfahrzeugen	U. Lehmann	Tabulated data does not include CO_2 or FC.	No useable data
A23	CARB Report (Dec. 1999)	1999	Air quality impacts of the use of ethanol in California reformulated gasoline (Final report to the California Environmental Policy Council)	B.E. Croes, P. Allen, R. Bradley, D. Luo, R. Vincent, L. Woodhouse	No new engine test data reported.	No useable data

Ref	Document	Year	Title	Author(s)	Information on Fuel Consumption	Key Conclusions
A24	CARB Report (Oct. 1998)	1998	Comparison of the effects of a fully-complying gasoline blend and a high RVP ethanol gasoline blend on exhaust and evaporative emissions	R. Cross, R. Summerfield, W. Loscutoff, P.D. Venturini, and T. McGuire	Exhaust emissions but no CO_2 or FC data reported.	No useable data
A25	IDIADA Report LM030411 (Sept. 2003)	2003	Comparison of vehicle emissions at European Union annual average temperatures from E0 and E5 petrol	R. Delgado, J. Izquierdo	The comparison is established between E0 and E5 in the NEDC. The following results are presented: urban phase – E0 FC is 9.99 l/100km and E5 FC is 9.78 l/100km. extra-urban phase – E0 FC is 6.70 l/100km and E5 FC is 6.77 l/100km. average – E0 FC is 7.91 l/100km and E5 FC is 7.87 l/100km. Difference in average FC is 0.5% and significant level of differences is 2%.	No significant difference in FC may be observed between E0 and E5. Difficult to reproduce their FC data when using estimated CWF data. Recalculations suggest 0.99% increase in mass FC from E5.
A26	AEAT Report E&E/DDSE/02/021 Issue 3 (March 2002)	2002	Ethanol emissions testing	A.H. Reading, J.O.W. Norris, E.A. Feest, E.L. Payne	E10 (9.5%v/v) comparison with gasoline. Statistical analysis excludes NEDC cycle - just real world (hot) cycles. Tables E2 and E4 gives 1.24% increase in fuel consumption (but decrease in CO_2).	FC was on average 1.24% higher with E10 (but only significant in 2 of 6 vehicles). CO_2 was on average 2.2% lower with E10 (and only significant in 3 of 6 vehicles).
A27	ADEME Report ETS 03-046 (Feb. 2003)	2003	Mesures d'émissions polluantes sur véhicules légers à allumage commandé, alimentés en carburants contenant de l'éthanol et de l'ETBE.	ADEME	MEVG Full Cycle: Significant vehicle to vehicle variability, and inconsistent between E5 and E10. For fleet average with E10 there is 2% higher mass FC (g/km), while typical fuel CalVal loss would be about 3.3%.	Fleet average over MVEG: FC (g/km) E5 +0.18% and E10 +2.19% CO_2 (g/km) E5 –1.58% and E10 –2.49%
A28	CRC E-67	2006	Effects of ethanol and volatility parameters on exhaust emissions	T.D. Durbin, J.W. Millar, et al.	In the fleet there was a 1.4% increase in volumetric fuel consumption (gal/mile) from E10, while the fuel tended to have a 2.2% reduced energy content. Estimated increase in mass FC is 3.7%, while reduction in LCV (MJ/kg) is 4.4%.	3.7% increase in mass FC from E10.

Ref	Document	Year	Title	Author(s)	Information on Fuel Consumption	Key Conclusions
A29	[3]		Joint EUCAR/JRC/CONCAWE study on: effects of gasoline vapour pressure and ethanol content on evaporative emissions from modern vehicles	G. Martini, et al.	E5 and E10 splash (S) and RVP-matched (E) blends in two separate base fuels (A and B). Over the vehicle fleet (7 cars) the increase in fuel consumption matched the reduction in calorific value. Note that not all fuels were tested in all vehicles, so some fuel effects relate to different vehicle numbers.	Fleet averaged over NEDC: A5S gave 2.8% higher mass FC; A10S gave 5.2% higher mass FC; A5E gave 2.4% higher mass FC; A10E gave 3.9% higher mass FC; B5S gave 2.0% higher mass FC; B10S gave 3.8% higher mass FC; B5E gave 1.3% higher mass FC; B10E gave 3.1% higher mass FC

In addition to the reports listed in **Appendix 1**, data were also taken from the JRC/EUCAR/CONCAWE (JEC) study on the effects of ethanol content on evaporative emissions [3], which is also Report A29 in the above table. This study included emissions tests over the NEDC on seven test vehicles. Fuel consumption was calculated from carbon balance. Carbon weight fraction and calorific value were derived from GC analysis of each fuel. The fuel matrix consisted of two base fuels, A and B, and eight additional test fuels. Four of the additional fuels were blended from each base fuel, generating 5% and 10% ethanol blends, both as splash blends and as RVP-matched blends.

The overall conclusion from the FC data in this fleet of vehicles was that the increase in FC directly corresponded to the loss in calorific value, thus indicating no change in engine thermal efficiency. Interestingly, it was noted that the two base fuels had almost identical calorific values (42.805 MJ/kg and 42.812 MJ/kg) although they did not have the same fuel consumption. The difference in results between these two base fuels was vehicle dependent. This implies that there could be an influence of fuel properties other than ethanol (or oxygen) content on the measured FC, which prompted the investigation of other datasets – see **Appendix 3**.

APPENDIX 2 CARBON BALANCE FUEL CONSUMPTION

A2.1. BASIC EQUATION

The fundamental equation for carbon balance fuel consumption is:

$$FC_m = \frac{\left(CWF_{Exh} \times HC + 0.429 \times CO + 0.273 \times CO_2\right)}{CWF_{Fuel}} \quad \text{in g/km} \qquad \text{(A1)}$$

Where:

- FC_m is the calculated mass fuel consumption in g/km
- CWF_{Fuel} is the carbon weight (mass) fraction of the fuel, e.g. 0.864 for a typical gasoline, but reduces significantly with the addition of ethanol
- CWF_{Exh} is the carbon weight (mass) fraction of the exhaust hydrocarbons
- *0.429* is the carbon weight (mass) fraction of CO (i.e. 12/28)
- *0.273* is the carbon weight (mass) fraction of CO_2 (i.e. 12/44)
- *HC* is the calculated HC emissions for the test in g/km
- *CO* is the calculated CO emissions for the test in g/km
- CO_2 is the calculated CO_2 emissions for the test in g/km

This equation will automatically produce results in g/mile, if all the emissions data are in g/mile. The equation can be applied to each phase of the test cycle or steady-state test sequence, or even to the second-by-second (modal) data as long as a fully consistent (time-aligned) set of emissions data are available.

This equation requires two pieces of information that are fuel related (CWF_{Fuel} and CWF_{Exh}). Since we do not generally measure CWF_{Exh} it is normally assumed that this is the same as CWF_{Fuel}. Alternatively, it is possible to use a constant (i.e. standard) value for CWF_{Exh}: It has very little impact on the overall calculation (since the majority of the Carbon is contained in the CO_2). However, it is evident that any error in CWF_{Fuel} will have a direct (proportional) effect on the calculated Fuel Consumption. Thus it is imperative that the correct CWF_{Fuel} value is used. The largest change in CWF_{Fuel} usually results from the use of oxygenated components such as ethanol. Since the CWF_{Fuel} reduces with the addition of oxygen, the fuel consumption will tend to be underestimated for an oxygen containing fuel if it is not correctly adjusted for the presence of oxygen. There is evidence that this error has occurred in more than one set of published data.

Converting the Mass Fuel Consumption (equation 1) to Volumetric Fuel Consumption requires the fuel density.

$$FC_v = \frac{FC_m}{SG_{Fuel} \times 1000} \quad \text{in litres/km} \qquad \text{(A2)}$$

Where:

- FC_v is the calculated volumetric fuel consumption in litres/km

- SG_{Fuel} is the density (specific gravity) of the fuel in kg/litre (i.e., 0.745 for typical gasoline).

The fuel consumption (FC) can be calculated in terms of the European units of litres/100km:

$$FC_{l/100km} = \frac{FC_m}{SG_{Fuel} \times 10}$$ in litres/100km (A3)

Fuel efficiency parameters (e.g. km/litre or km/gram) can be simply calculated by inverting equations (2) and (3). However if the UK or US formats of miles/gallon are required, some additional factors are also needed:

- 1.6093_{44} km/mile
- 4.5461 litres/Imperial Gallon
- 3.7854 litres/US Gallon

This results in the following equations:

$$MPG_{UK} = \frac{4.5461}{FC_v \times 1.6093}$$ in miles/Imperial Gallon (A4)

$$MPG_{US} = \frac{3.7854}{FC_v \times 1.6093}$$ in miles/US Gallon (A5)

A2.2. EPA GASOLINE EQUATION

For US gasoline vehicle tests (e.g. FTP tests), the equation used for fuel economy calculations (and referenced to the EPA and the federal register) is:

$$MPG_{US} = \frac{5174 \times 10^4 \times CWF \times SG}{(CWF \times HC + 0.429 \times CO + 0.273 \times CO_2) \times ((R_f \times SG \times NHV) + 5471)}$$ (A6)

Where:

- *MPG_{US}* is the calculated fuel efficiency in miles per US-gallon
- *CWF* is the carbon weight (mass) fraction of the fuel. Note that the same value is used for both the fuel and the exhaust gas HC.
- *SG* is the specific gravity (density) of the fuel in kg/litre
- *0.429* is the carbon weight (mass) fraction of CO (i.e. 12/28)
- *0.273* is the carbon weight (mass) fraction of CO_2 (i.e. 12/44)
- *HC* is the calculated HC emissions for the test in g/mile
- *CO* is the calculated CO emissions for the test in g/mile
- *CO_2* is the calculated CO_2 emissions for the test in g/mile
- *R_f* is stated as “The ‘R’ factor as described in Federal Register Vol. 51, used to account for sensitivity of vehicular fuel economy to heat energy of test fuel”. The typical value used for gasoline is 0.6.
- *NHV* is the Net Heating Value (Net Calorific Value) in Btu/lb

The above equation (A6) can be expressed (by simple manipulations) in two components:

$$MPG_{US} = \frac{\left(CWF \times SG \times 10^3 \times 3.7854\right)}{\left(CWF \times HC + 0.429 \times CO + 0.273 \times CO_2\right)} \times \frac{10^1 \times 1366.83}{\left(\left(R_f \times SG \times NHV\right) + 5471\right)} \quad \text{(A7)}$$

This manipulation is performed so that the left-hand component of this equation represents the fundamental equation for the carbon balance fuel efficiency, derived from a combination of equations (1), (2) and (5). In the above formulation, the factor 1.6093 is removed since the emissions are already in g/mile (not g/km), while the factor of 3.7854 converts litres to US-gallons.

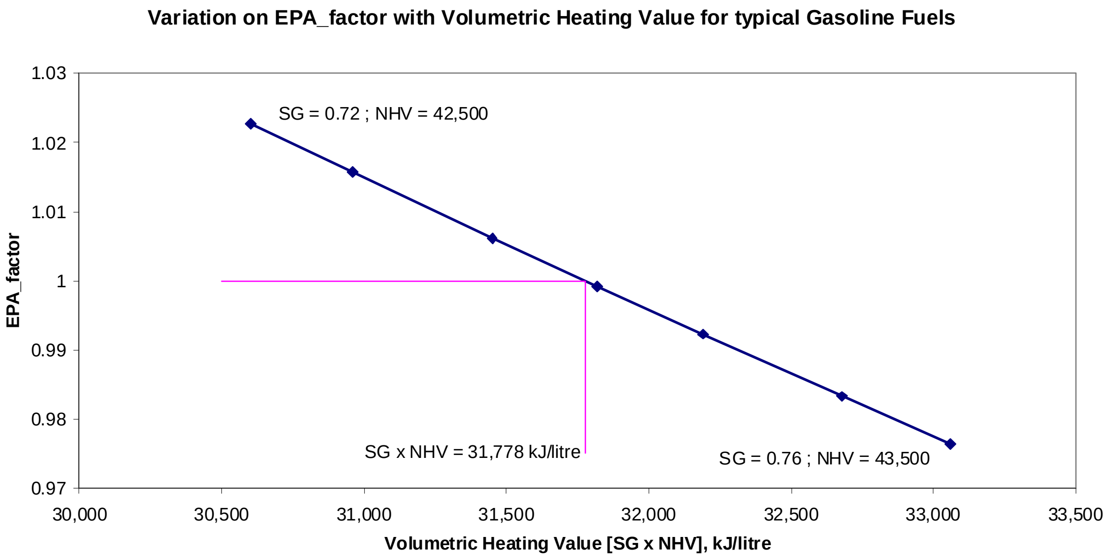
The right-hand component is an empirical factor which corrects the fuel efficiency depending on the NHV of the test fuel. Thus, if a fuel of high NHV is used, there is a correction downwards in the fuel efficiency, and vice versa. Further understanding of the nature of this correction factor is given below.

This factor is given the name (in this Appendix) of “EPA_{factor}”. Thus:

$$EPA_{factor} = \frac{13668.3}{\left(\left(R_f \times SG \times NHV\right) + 5471\right)} \quad \text{(A8)}$$

Taking some typical values of R_f (0.6), SG (0.740 kg/litre) and NHV (18487 Btu/lb, which is equivalent to 43000 kJ/kg), this factor comes out as 0.9992. So for this typical fuel, the difference between the fundamental carbon balance FC and the EPA equation is less than 0.1%. **Figure A2.1** shows the potential variation in this factor for a range of typical fuels, when R_f is taken as 0.6. In this case, the factor varies by about ±2% from unity.

Figure A2.1. Variation in the calculated EPA_{factor} with gasoline fuel properties (in terms of the Volumetric Heating Value)

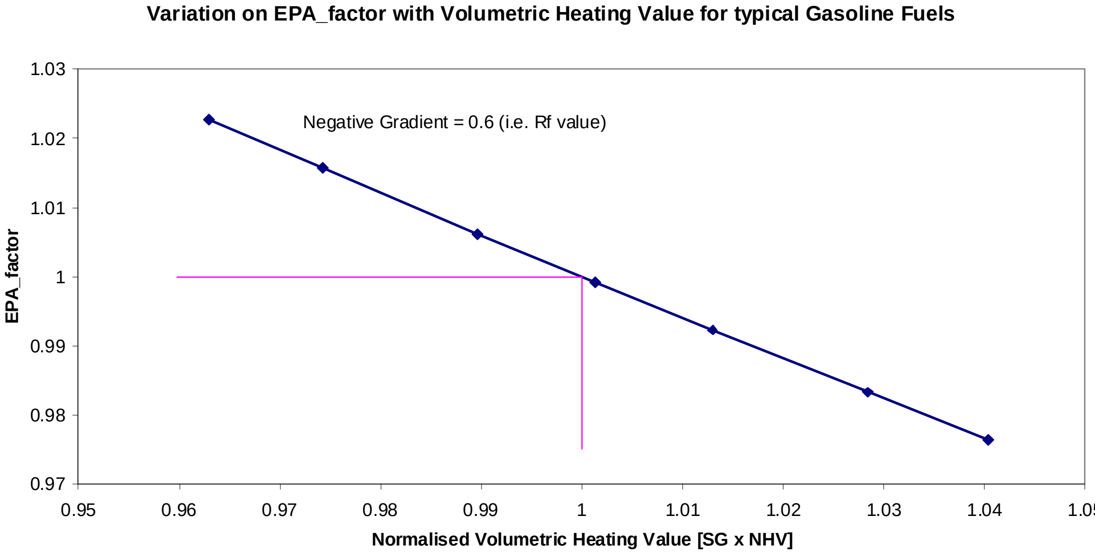


In **Figure A2.1**, the highest value of the factor is given by the fuel properties SG 0.72 kg/litre and NHV 42,500 kJ/kg (resulting in a volumetric heating value of 30,600 kJ/litre) and the lowest value of the factor is given by the fuel properties SG 0.76 kg/litre and NHV 43,500 kJ/kg (resulting in a volumetric heating value of

33,060 kJ/litre). The factor has a value of 1.0 when the volumetric heating value is 31,778 kJ/litre.

The same data can be plotted with a normalised x-axis, as shown in **Figure A2.2**. Over this relatively small range of x- and y-values, the data lie almost on a straight line, with a gradient equal to $-R_f$ (i.e., –0.6).

Figure A2.2 Variation in the calculated EPA_{factor} with gasoline fuel properties (in terms of the relative Volumetric Heating Value)



The interpretation of this empirical factor (equations 7 and 8) is based on some rounded constants. Looking at the form of the factor, it is likely that when the properties for the reference fuel are used, and R_f is 0.6 the factor should equate to:

$$EPA_{factor} = \frac{x}{(0.6x + 0.4x)} \tag{A11}$$

Thus the constant 5471 should equate to 0.4***x*** which gives ***x*** = 13677.5. Thus it is proposed that the more correct form of the factor might be:

$$EPA_{factor} = \frac{13677.5}{((R_f \times SG \times NHV) + 5471)} \tag{A12}$$

The difference between the constants 13677.5 in equation 12 and 13668.3 in equation 10 is only 0.07%, and may have resulted from the rounding of a conversion factor such as litres per US Gallon.

With this form of the equation, and R_f = 0.6, the factor should be equal to 1.0 when:

$$SG \times NHV = 31814 \quad \text{in kJ/litre} \tag{A13}$$

With the factor R_f = 0.6, this suggests that only 60% of the change in volumetric heating value is actually seen as a volumetric fuel consumption change. There may be thermodynamic reasons why the other 40% of the change in volumetric heating value is lost within the engine operation, and may relate to correlated changes in the HC type which could affect octane and stoichiometric air/fuel ratio. If this factor has been defined experimentally on older US vehicles (prior to 1986), it is possible that this factor is not appropriate to current vehicle populations around the world.

APPENDIX 3 RESULTS FROM CONCAWE TEST PROGRAMMES

A3.1. JEC EVAPORATIVE EMISSIONS PROGRAMME

This section discusses results from a JEC Consortium study on evaporative emissions from seven gasoline vehicles [3].

The measured variation in mass fuel consumption with fuel calorific value is shown in the following figures for each of the seven vehicles. For all seven vehicles, there is an overall trend for the mass fuel consumption to reduce as the fuel calorific value increases. The figures also include lines of constant energy consumption. The two outside lines are +1% and –1% energy consumption relative to the middle line. For the Ford Focus (A3.1.1) and the Toyota Corolla (A3.1.4), the reduction in fuel consumption with increasing fuel calorific value is less than would be expected from a constant energy hypothesis, although for both vehicles there is possibly one fuel (circled in figures) that lies significantly off the overall trend, and could be having a large impact on the outcome. The VW Golf (A3.1.6) shows the opposite trend and is more responsive to fuel calorific value than would be expected from a constant energy hypothesis. However, this data set also contains one very low fuel consumption fuel (circled), which appears to be driving this outcome.

The other four vehicles all show responses that are relatively close to the constant energy hypothesis. Apart from one fuel in each of the three cases mentioned above (Focus, Corolla and Golf), the spread of fuel data is about +/-1% to +/-1.5% from a constant energy hypothesis. Within this fuel set, the variation in fuel calorific value is just under 4% (base fuel to E10). With this level of noise to signal, the correlation coefficients (R^2) are only about 0.7 at best. The analysis contained within the JEC report estimates a 3.97% increase in fuel consumption from an E10 blend, across the fleet, compared to a calculated energy loss of 3.4%.

Figure A3.1.1 Ford Focus: trend appears to be different from the iso-energy lines, although one fuel (circled) lies well away from the main set of data points

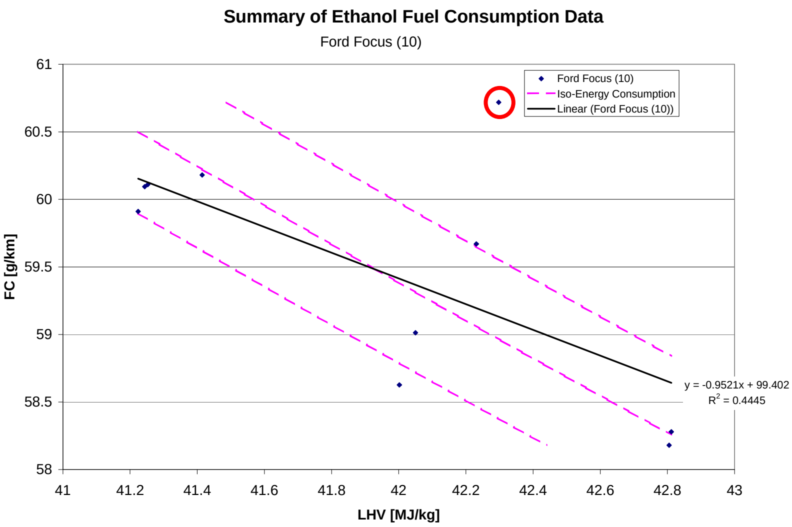


Figure A3.1.2 VW Polo: the overall trend is similar to the iso-energy line

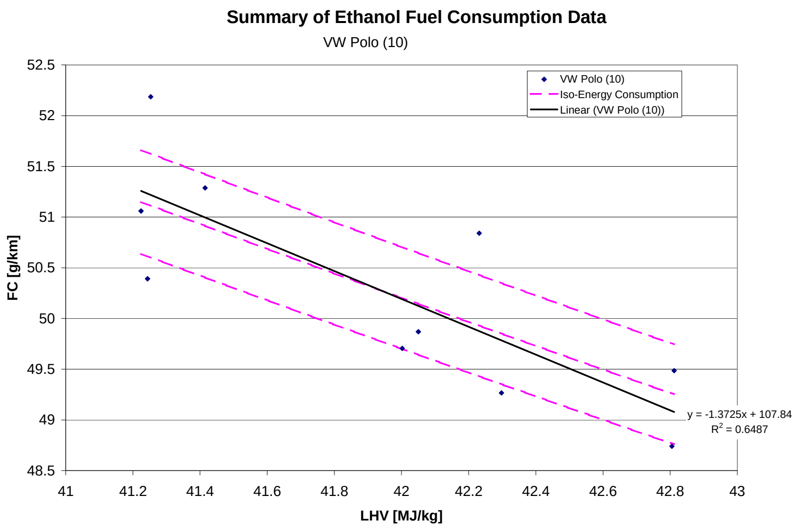


Figure A3.1.3 Renault Megane: the overall trend is similar to the iso-energy line

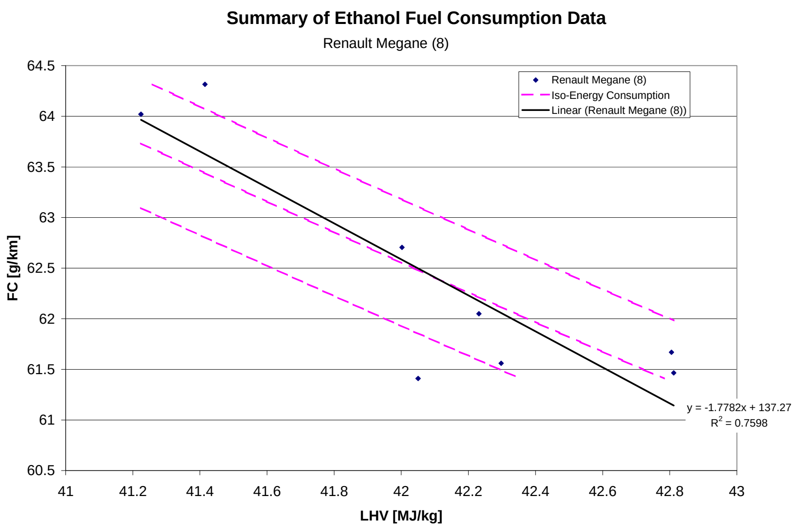


Figure A3.1.4 Toyota Corolla: trend appears to be different from the iso-energy lines, although one fuel (circled) lies well away from the main set of data points

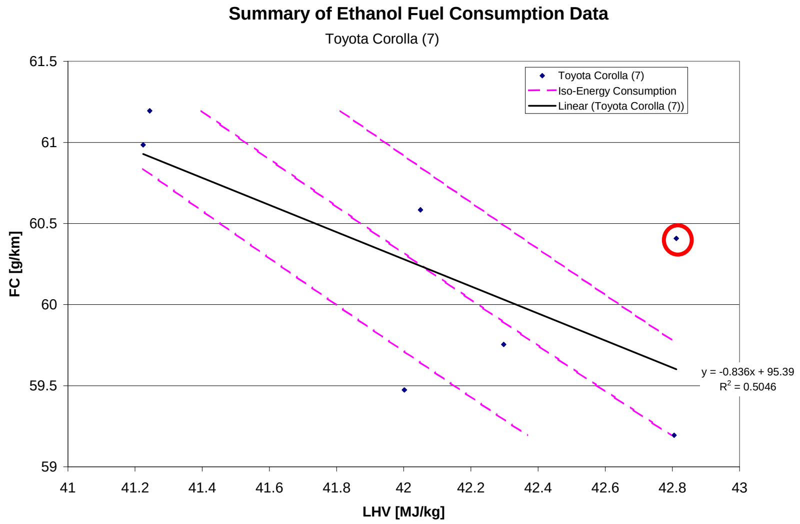


Figure A3.1.5 Lancia Y10: overall trend is similar to the iso-energy line

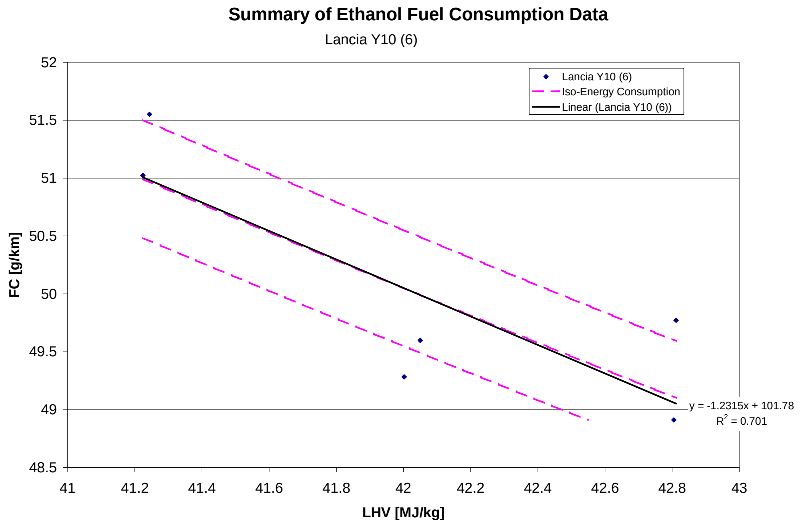


Figure A3.1.6 VW Golf: trend appears to be different from the iso-energy lines, although one fuel (circled) lies well away from the main set of data points

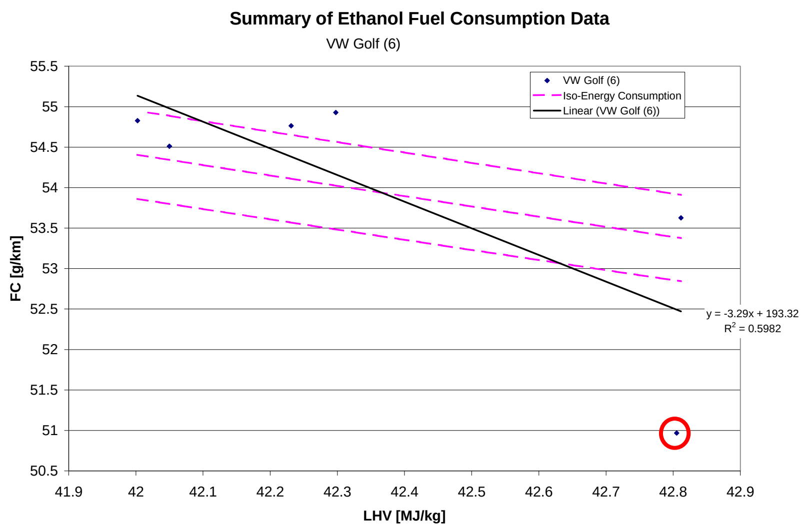
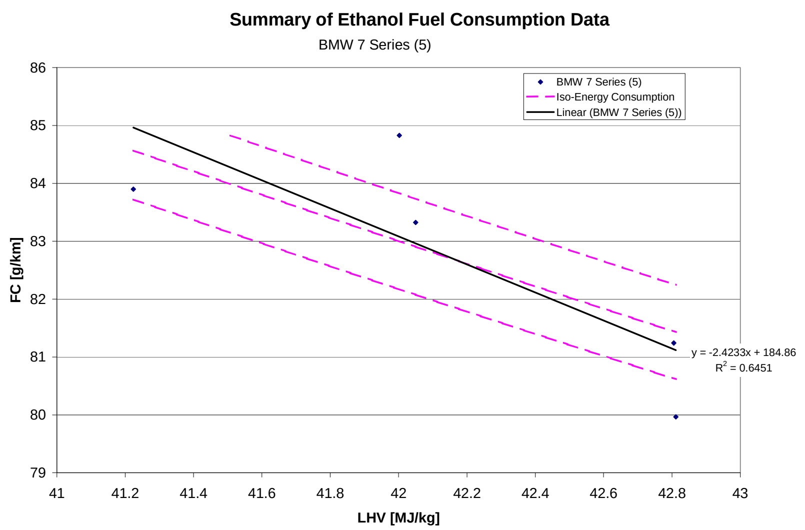


Figure A3.1.7 BMW 7 series: overall trend is similar to the iso-energy line



A3.2. CONCAWE GASOLINE EMISSIONS PROGRAMME

This section discusses results from a CONCAWE study on regulated emissions from four gasoline vehicles [4].

The measured variation in mass fuel consumption with fuel calorific value is shown in the following figures for each of the four vehicles. For all four vehicles, there is an overall trend for the mass fuel consumption to reduce as the fuel calorific value increases. The figures also include lines of constant energy consumption. The two outside lines are +1% and –1% energy consumption relative to the middle line.

For Car A (A3.2.1) and Car C (A3.2.3), the change in fuel consumption with fuel calorific value does not follow the iso-energy trend: In both cases, the trend fitted to the measured data is probably influenced by one or two results for the low calorific value fuels, which are giving low fuel consumption and high calorific value fuels, which are giving high fuel consumption. Red circles on the figures highlight these points. For both of these vehicles, the relationship between fuel consumption and calorific value is not significant at the 95% confidence level.

For the other two cars, the overall trend given by the data is very close to the iso-energy line and the relationship between fuel consumption and calorific value is significant at the 95% confidence level. For these two cars, almost all of the data lie within the +/-1% iso-energy lines. For Car A and Car B, this would also be the case if the points circled in red were omitted.

Figure A3.2.1 Car A: overall trend appears to be different from the iso-energy line, mainly due to the lower fuel consumption of the low calorific value fuel and the higher fuel consumption of two high calorific value fuels (three circles)

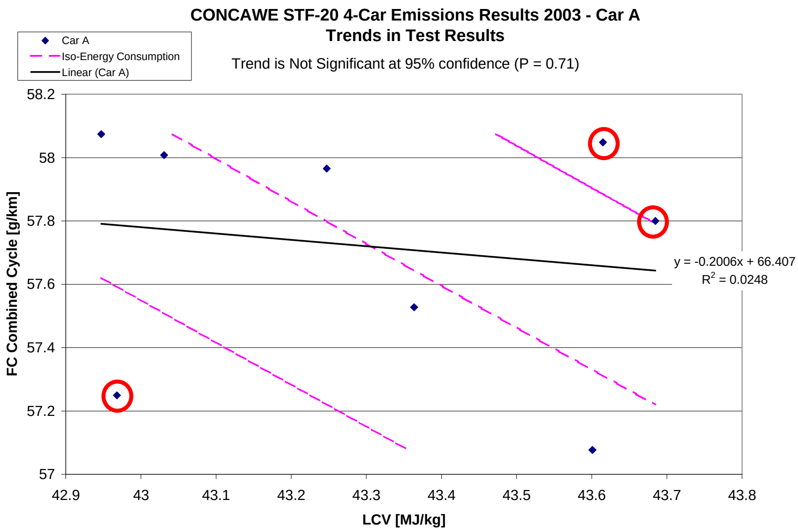


Figure A3.2.2 Car B: overall trend is similar to the iso-energy line

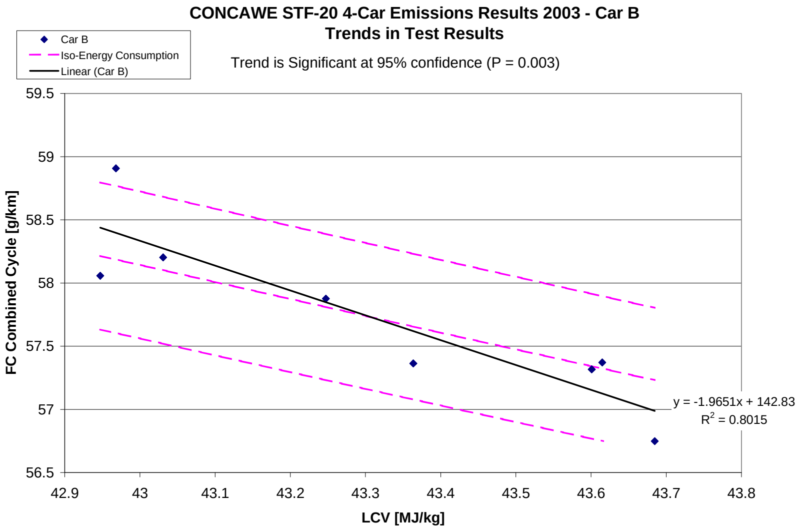


Figure A3.2.3 Car C: overall trend appears to be different from the iso-energy line, mainly due to the lower fuel consumption of the two low calorific value fuels (two circles)

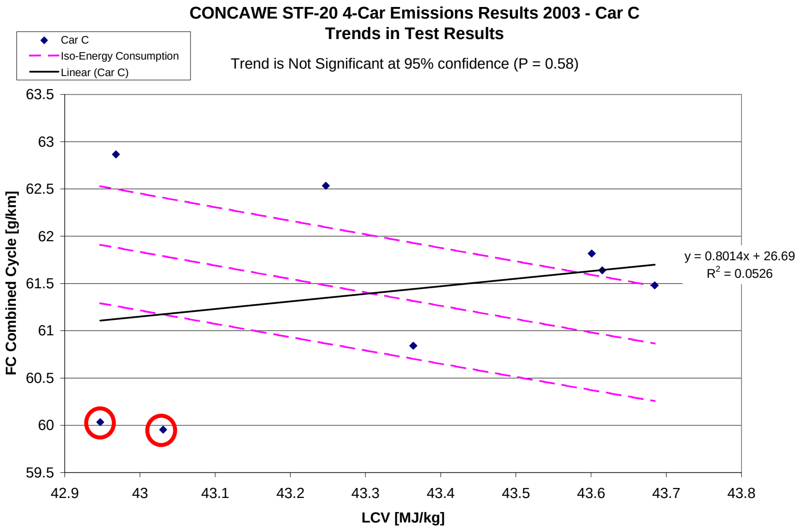


Figure A3.2.4 Car D: overall trend is very similar to the iso-energy line

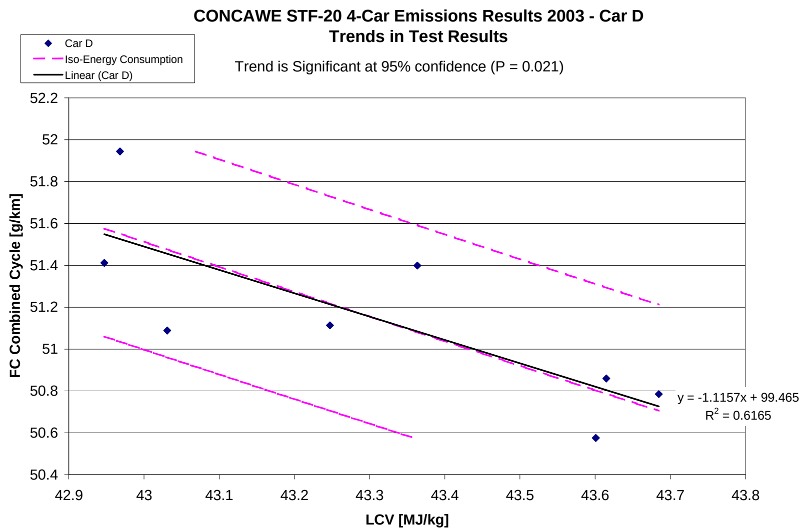
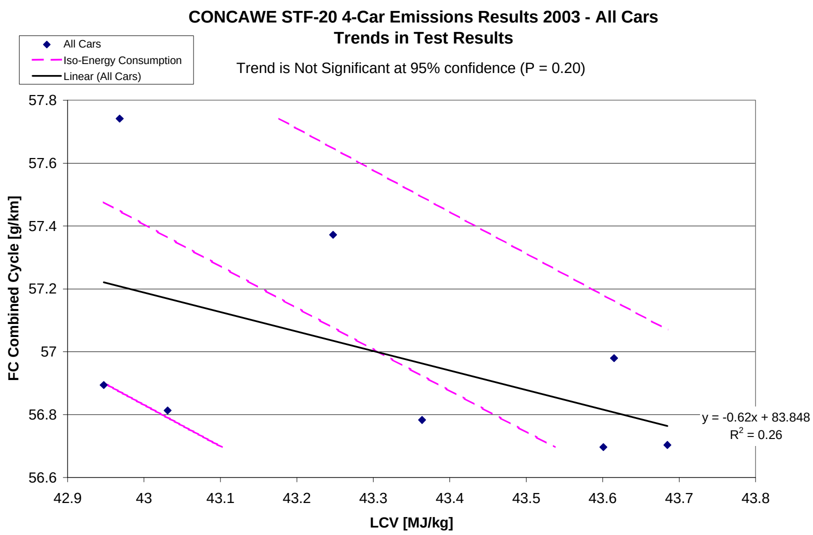


Figure A3.2.5 Mean of 4 cars: overall trend is somewhat similar to iso-energy line, but the relationship reflects the poor response of Cars A and C



CONCAWE
Boulevard du Souverain 165
B-1160 Brussels
Belgium

Tel: +32-2-566 91 60
Fax: +32-2-566 91 81
e-mail: info@concawe.org
website: http://www.concawe.org

ISBN 978-2-87567-032-8
9 782875 670328 >