A Literature Review Based Assessment on the Impacts of a 20% Ethanol Gasoline Fuel Blend on the Australian Vehicle Fleet.

Report to
Environment Australia

November, 2002.

Orbital Engine Company

CONTENTS

1 EXECUTIVE SUMMARY

This report represents part of the work commissioned by Environment Australia (EA) under tender 34/2002 “Environment Australia Project: ‘Market Barriers to the Uptake of Biofuels – Testing Petrol Containing 20% Ethanol (E20)’”. Specifically, this report satisfies the section of work Section 2.3.10.2 titled “Analysis of Impacts”.

A study has been conducted on the suitability of ethanol/gasoline blend fuels that contain greater than 10% (by volume) ethanol. The study has focused on researching effect of high ethanol blend fuels on noxious and greenhouse emissions, vehicle operability and engine and fuel system durability. The study needs to be considered in the context of the current vehicle fleet, which must operate effectively and efficiently on the 20% ethanol blend without re-tuning/recalibration or other modification. In many cases, there is insufficient or conflicting information available, indicating the detailed testing program, which is to be undertaken as part of tender 34/2002, is warranted.

The addition of ethanol increases the available oxygen for combustion. Older vehicles with open-loop fuel systems suffer enleanment of the combusted mixture. The net effect on legislated emissions would be a reduction in carbon-monoxide (CO) emissions. The effect on unburnt hydrocarbon (HC) and oxides of nitrogen (NOx) emissions is more complex, and is dependent on the engine calibration.

Vehicles fitted with closed loop fuel systems and three-way catalyst (TWC) systems show reduced CO emissions, and generally reduced total HC emissions with an ethanol content beyond 20%. Tailpipe NOx emissions increased by approximately 30% with a 20% ethanol blend compared with no increase for a 10% blend. The 30% increase in NOx corresponds to approximately 10 to 15% of the current Australian NOx emissions regulation for passenger vehicles, but could be as much as 50% of the new proposed emissions regulation (ADR 79/00).

The available data on unregulated emissions for ethanol blends greater than 10% is small. Aldehyde emissions will increase as the percentage of ethanol increases. Predominantly, this is due to acetaldehydes increasing by more than 100% with ethanol blends of 10%. Formaldehyde emissions will remain relatively constant. Other unregulated emissions of toxic and greenhouse gases are unlikely to change.

Carbon dioxide (CO_2) emissions reductions for 20% ethanol blends are reported to be small and may not be significant when considering the total fuel cycle. The ethanol production process may dominate any small reductions in vehicle tailpipe levels. In the case of vehicle fuel economy, this may fall by approximately 7% for a 20% ethanol blend. This loss is primarily due to the reduction in energy content of the 20% blend.

Evaporative emissions are likely to increase with higher blends of ethanol, with increasing evaporative emissions measured during vehicle “hot soak” testing. Future Australian emissions legislation will include a further “real time diurnal test” which is highly likely to exacerbate the problem. The E20 blend may increase evaporative emissions by vapour permeating through some fuel system plastics.

Vehicle operability may deteriorate with 20% ethanol blends. Those vehicles fitted with lean calibrated carburettors are likely to display the most significant deterioration across the driveability spectrum due to enleanment. For those vehicles fitted with closed loop fuel injection systems, enleanment is likely to deteriorate the cold start performance and warm up. However this is likely to be dependent on the ability of the engines control system to maintain stoichiometry, a function related to the manufactures control strategy. In terms of hot weather driveability, the newer vehicle fleet should be more robust though this is most dependent on the design of the fuel system.

The anti-knock capability of high ethanol blends is not as simple as defined by the standard measurements of Research and Motor Octane Numbers, (RON & MON). Testing suggests that there is either a negative or at best a marginal benefit with ethanol blends beyond 5% by volume. It is likely that high engine speed knock will occur due to the increase in octane sensitivity of the 20% ethanol blend. Vehicles fitted with knock sensors will not exhibit the associated “pinging” sound, though depending on the reduction in spark advance may suffer reduced acceleration performance.

The impact of a 20% ethanol blend on engine and fuel system durability of the Australian vehicle fleet is unclear. In terms of engine wear the literature reviewed is vague, leaving the only valid conclusion that testing is required to obtain data to form a view. The literature studied indicates that there is a significant potential problem for those vehicles with fuel systems that have reached the ‘normal’ stabilised level of internal deposits, which are passive to gasoline. Upon introducing these vehicles to a 20% ethanol blend, these deposits are likely be stripped away causing fuel filter blockages and plugging of fuel metering components.

Perishing and swelling of elastomeric and plastic materials making up the fuel system is highly likely on the older vehicle fleet when exposed to E20. The newer fleet may be less likely to show these problems as many of the components are globally sourced and therefore may be compatible with up to 10% ethanol blends providing some element of protection for an E20 blend. Whenever there is any potential for a fuel leak, a potentially hazardous situation is created.

The potential for corrosion of the metal components of the fuel system has also been identified by this literature study. Metal surfaces within the fuel system must be specifically treated to guard against corrosion with the E20 blend. This is likely to be a longer term issue as the corrosion process is relatively slow, however the potential for a fuel leak is clear.

It is expected that the issues and shortcomings in information for E20 blends identified in this report will be appropriately addressed and reported in due coarse by the execution of the scope of work provided within the Orbital Engine Company tender 34/2002. This is assuming that the 80,000km vehicle mileage accumulation is undertaken as part of the EA Project.

2 INTRODUCTION

The Commonwealth Government of Australia, represented by Environment Australia (EA), is investigating the effects of higher ethanol blends in fuel on the Australian vehicle fleet. This investigation is to provide information to the Government on the impacts of noxious and greenhouse emissions, vehicle performance and durability from the use of 20% by volume ethanol blended with gasoline (E20). This study will then be used to aid the Government to set the national fuel standards as provided by the *Fuel Quality Standards Act 2000*.

EA, under the auspices of the Ethanol task force, commissioned an issues paper with the aim of seeking public comment on setting the appropriate ethanol limit in automotive fuel (1). This paper extensively covered the issues related to using ethanol as an automotive fuel. In particular it refers to two earlier trials conducted in Australia. The first trial in 1980-83 (24) examined the impacts of E15 (15% ethanol). The second in 1998 (23) comprised an intensive field trial of ethanol/gasoline blend E10 (10% ethanol) in vehicles. The data from these trials, plus evidence from the submissions to the issues paper, lead to the conclusion that generally blends up to 10% are accepted as being suitable for the Australian fleet. Currently, however, there is not general consensus on the applicability of higher ethanol concentration blend fuels for the Australian vehicle fleet.

One of the conclusions that can be drawn from the submissions to the issues paper was the lack of current Australian data on the effects of higher ethanol blends (E20) on the Australian fleet. In order to rectify this, EA has commissioned testing on vehicles and components under tender No. 34/2002.

As part of this tender, EA requested a study on the available data on higher ethanol blends and the impacts on noxious and greenhouse gas emissions, vehicle operability and engine and fuel system durability with blends greater than 10% ethanol compared to straight gasoline. The following report is an assessment of the pertinent testing results and available data on the impact of higher ethanol blends. This report, in conjunction with the FMEA report, aims to verify that the scope of work to be performed on the vehicle and component testing (also covered by the same tender using E20 by Orbital Engine Company) is both warranted and sufficient to identify major issues associated with the adoption of higher ethanol blend fuels.

3 ENVIRONMENTAL ASPECTS OF HIGHER BLEND ETHANOL FUELS

Motor vehicles can have a significant (detrimental) contribution to air quality in most urban areas. This contribution is mainly from exhaust gas and evaporative emissions which contain noxious and greenhouse gases. These include typical legislated emissions such as unburnt hydrocarbons (HC), oxides of nitrogen (NOx) and carbon monoxide (CO). As well as these, there are greenhouse gas and other toxic emissions, which include carbon dioxide (CO_2) (a product of combustion of hydrocarbon based fuels which is therefore also linked to vehicle fuel consumption), CH_4, N_2O, fine particulate matter, aldehydes (formaldehyde and acetaldehyde), benzene, 1,3-butadiene, polycyclic organic matter (POM) and others.

3.1 Fuel Property Changes with Ethanol Addition

The addition of ethanol to gasoline results in changes to the properties of the fuel. When fuel properties change they can affect the vehicle performance in many ways. This includes exhaust and evaporative emissions, fuel economy, driveability, full load performance (power) and durability. The extent to which changes in fuel composition affects these vehicle performance qualities are very dependent on the vehicle itself, including engine design, fuel system and control system, as well as emissions control equipment.

Table 1 summarises the some of the major properties of gasoline, ethanol, and mixtures of 10% and 20% (by volume) ethanol with gasoline. This is assuming splash blending of the components with no special blend stock for the gasoline component.

Property	Gasoline	Ethanol	10% Ethanol / Gasoline Blend	20% Ethanol / Gasoline Blend[2]
Specific Gravity @ 15.5 °C	0.72 - 0.75	0.79	0.73 – 0.76	0.735 – 0.765
Heating Value (MJ/kg) (BTU/lb)	 43.5 18,700	 27.0 11,600	 41.9 18,000	 40.0 17,200
Heating Value (MJ/litre) (BTU/gal)	 32.0 117,000	 21.3 76,000	 30.9 112,900	 29.9 109,000
Approx Reid Vapour Pressure @ 37.8ºC (kPa)[1]	59.5	17	64.0	63.4
Stoichiometric Air/Fuel Ratio	14.6	9	14	13.5
Oxygen Content (% by weight)	0.00	35	3.5	7.0

Table 1 – Properties of Gasoline, Ethanol and Gasoline/Ethanol Blends (1); except for [1] (5) and [2] from calculation)

The effect of adding ethanol to gasoline is to oxygenate the fuel. The higher the ethanol blend, the higher the oxygen content in the fuel. Figure 1 shows the linear increase in oxygen as the % of ethanol is increased (5). The increased oxygen in the fuel changes the stoichiometric air/fuel ratio of the fuel. The stoichiometric air/fuel ratio is the chemically correct or theoretical air to fuel ratio which provides the minimum amount of oxygen for the conversion of all the fuel into completely oxidised products. (For a hydrocarbon-based fuel, this means that all the carbon in the fuel is converted to CO_2 and the hydrogen to water, H_2O). If there is no compensation for this change in stoichiometric air/fuel ratio and the engine is operated at the same mass air/fuel ratio, there is, in effect, a change to the mixture strength as the ethanol content in the fuel is increased. Mixture strength is normally referred to in two non-dimensionalised terms. The first is equivalence ratio, which is the ratio of the theoretical stoichiometric air/fuel ratio and the actual air/fuel ratio, ie:

$$\text{Equivalence Ratio, } \phi = (\text{Stoichiometric A/F Ratio})/(\text{Actual A/F Ratio}).$$

As the mixture becomes more fuel rich (mixture strength increases), the equivalence ratio is increased.

The other term often used is relative air/fuel ratio (or lambda), often expressed as the symbol λ. The relative air/fuel ratio is the inverse of the equivalence ratio; that is:

$$\lambda = (\text{Actual A/F Ratio})/(\text{Stoichiometric A/F Ratio})$$

As the mixture becomes fuel rich, the relative air/fuel ratio is reduced.

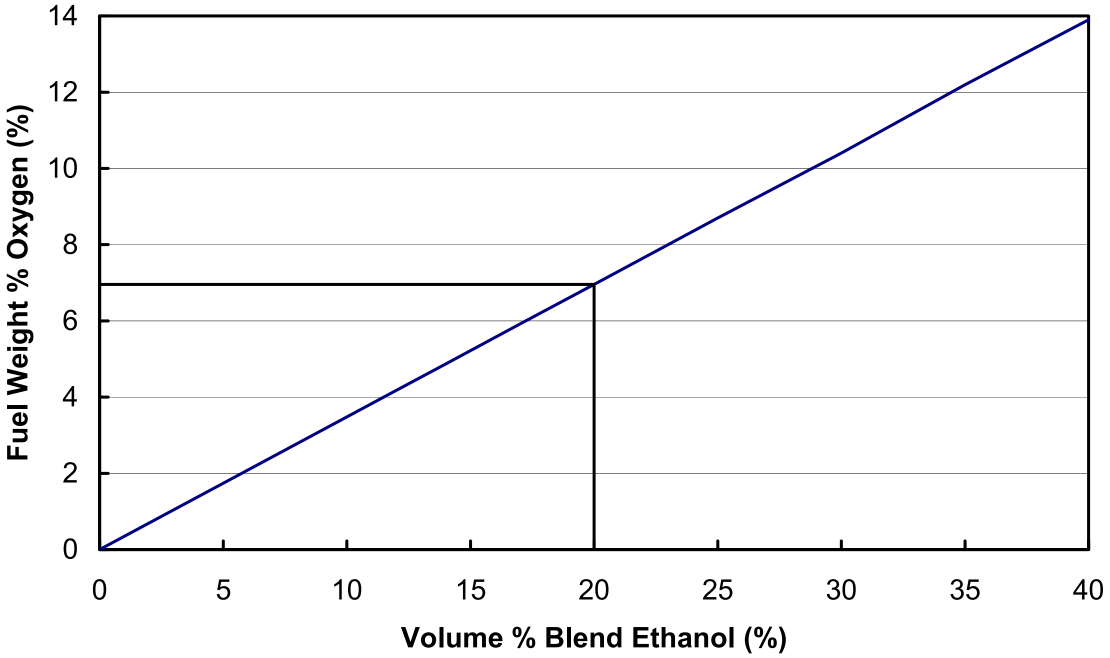


Figure 1 – Oxygen content for ethanol blended fuels

Figure 2 shows how the mass air/fuel ratio corresponding to stoichiometric ($\lambda=1$) mixture strength changes with the addition of ethanol to gasoline. From this figure, it is clearly seen that gasoline has a stoichiometric air/fuel ratio of approximately 14.6:1, while a 20% blend of ethanol and gasoline has a stoichiometric air/fuel ratio of approximately 13.5:1. Also shown in this figure is the fuel metering characteristic line. As a first approximation, it is assumed that most fuel systems (without compensation) will deliver approximately the same volume of fuel (regardless of the fuel composition). This is especially true for electronic fuel injection systems. Therefore, changes in fuel density will change the mass of fuel delivered. As ethanol has a higher density than gasoline, as the ethanol content is increased, the fuel mass is increased for a given injection system setting. By definition, this increase in mass results in a reduction of the mass air/fuel ratio, as is shown by the fuel metering characteristic line. This increase in mass partially compensates (but nowhere near sufficiently) for the reduction in stoichiometric air/fuel ratio as the ethanol content increases (4).

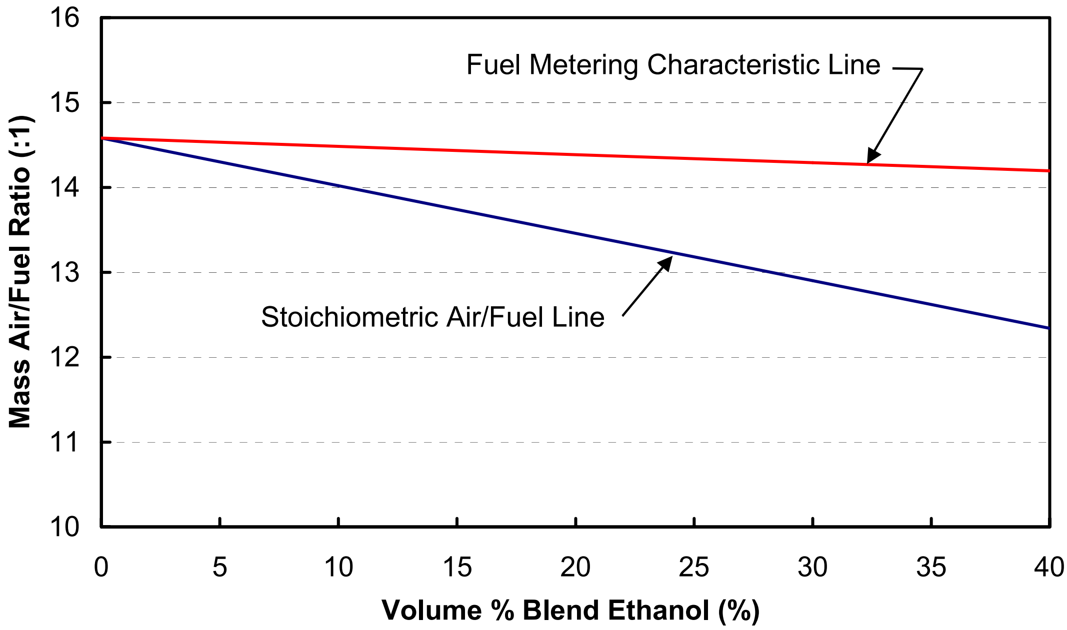


Figure 2 - Stoichiometric air/fuel ratio of ethanol blended fuel

Figure 3 shows how the relative air/fuel ratio (λ) of the mixture changes with change in ethanol content for a constant volume of fuel delivered. It is assumed that the volume ratio of air and fuel equates to a stoichiometric mass air/fuel ratio, ie λ = 1 for gasoline only fuel. As the ethanol content increases, the mixture becomes (fuel) leaner for the same volume of fuel delivered, as demonstrated by the increase in lambda. This phenomenon is also often referred to as "enleanment" of the mixture (11).

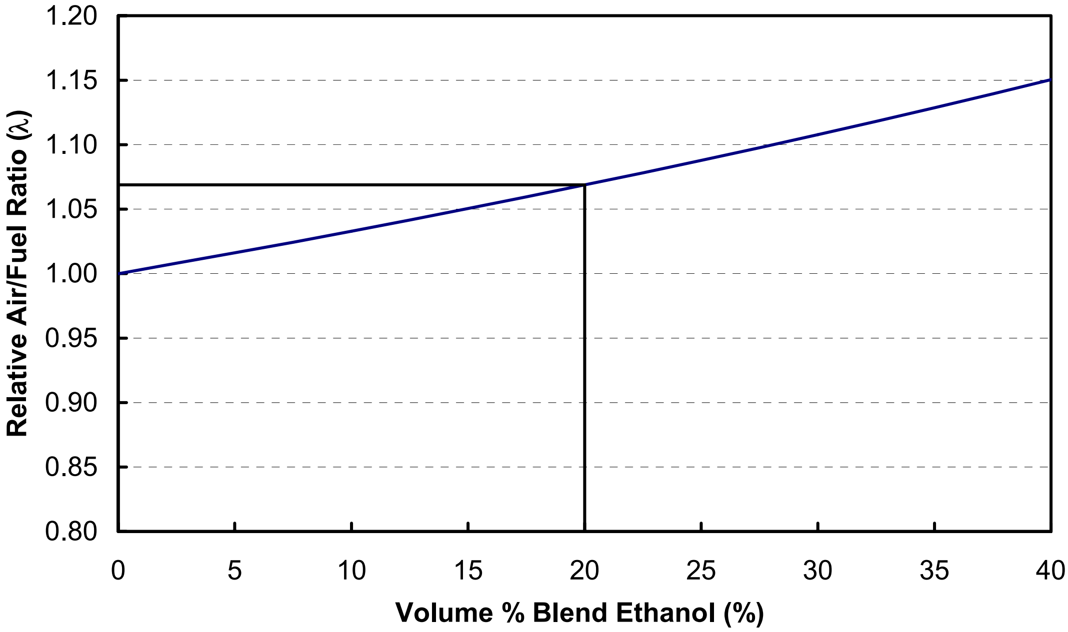


Figure 3 – Relative Air/Fuel ratio (λ) vs ethanol blend for constant fuel delivery volume

At a 20% by volume ethanol blend with gasoline, the enleanment is seen to be approximately 7%. For combustion of homogeneous mixtures, the mixture strength plays a significant role in terms of the "quality" (stability and controllability of the combustion event) and the products of the combustion process. These effects will be further explained in the subsequent section on noxious emissions generation (see section 3.3.1). In order to minimise the changes in the combustion process, it is desirable to maintain the same mixture strength with the different fuel blends.

3.2 Fuel System & Control System Definitions

In general, the fuel system & control system technology employed in light-duty vehicle fleets can described by one the following four technology groups:

- Open-loop carburetted
- Closed-loop carburetted
- Open-loop fuel injected
- Closed-loop fuel injected

When considering the impact of changes in fuel properties on emissions and driveability, these fuel (and control) systems can best be divided into two classes; these being “open-loop” and “closed-loop”. Open and closed-loop refers to control terminology, with the loop describing the type of control strategy employed. For an open-loop system, the input to achieve a desired output is independent of the actual output. For a closed-loop system, the input is dependent on the output. This is achieved via some feedback mechanism to the control system, i.e. some output quantity is measured and compared to the desired output. The difference between the two is used to change the input to in order to achieve the desired output.

In the case of the fuel system, this is accomplished via the use of a feedback sensor, which measures directly the oxygen content in the exhaust. This measurement can then processed and used to determine the air/fuel ratio. If the measure of air/fuel ratio varies from the desired air/fuel ratio, then the fuel delivery can be adjusted to bring the measured air/fuel ratio into range.

3.2.1 Open Loop Fuel Delivery Systems

Prior to 1986, the emissions standards in Australia made it possible for vehicles to be equipped with fuel delivery systems such as open-loop carburettors or open-loop fuel injection systems. Typical fuel delivery systems are essentially volume flow devices. For a given engine state (airflow), the volume of fuel delivered to the engine will be the controlled in order to achieve a desired (target) equivalence ratio for the combustion process. As there is no feedback loop with these open-loop systems, the volume of fuel delivered by the fuel system for a given engine condition will remain constant. This means that changes in fuel properties such as density and chemical composition will change the delivered (actual) equivalence ratio for these systems. Generally, these open-loop systems are designed to be tolerant to some changes in equivalence ratio, as well as a having a manual mixture strength tuning ability (idle mixture strength screw for carburettors, or a potentiometer for open-loop electronic fuel injection systems). This is to allow for errors in the system due to deterioration/ageing, environmental conditions (altitude, market fuel etc), and system build tolerances. The addition of ethanol to gasoline changes the density and stoichiometric air/fuel ratio of the fuel. The stoichiometric air/fuel ratio is reduced (including the volume based air/fuel ratio given that ethanol is slightly more dense than gasoline alone), and as such, the mixture strength for a given volume of fuel delivered to the engine, will be reduced, ie enleanment will occur (see Figure 3). The possible effects of this enleanment are discussed in following sections.

There are a number of vehicle models in the Australian fleet, which not only have open loop fuel systems but are also fitted with oxidation catalysts for CO and HC emission control. The oxidation efficiency is sensitive to the oxygen storage capability of the catalyst. This capability is defined by the wash-coat technology (the wash-coat being the slurry that is applied to the surface of the ceramic substrate of a catalyst). Higher oxygen content in the exhaust gas will have the effect of filling the catalyst faster and enhance the oxidation efficiency. As the oxidation process is exothermic there may well be an increase the catalyst temperature. The effect in real world conditions is difficult to predict however thermal degradation is one of the main causes of catalyst failure.

3.2.2 Closed Loop Fuel Delivery Systems

As tailpipe emissions legislation became increasingly more stringent the post treatment of exhaust gases became imperative. The most commonly used and effective aftertreatment method for spark ignition engines is the lambda closed loop control systems coupled with three way catalyst (TWC) systems. These systems are able to reduce the engine-out HC, CO and NOx emissions by more than 98% provided the engine operates at air/fuel ratios within approximately 2% of the stoichiometric air/fuel ratio ($\lambda = 1$). This very small tolerance range is unable to be maintained without closed loop control systems, even for modern, high precision fuel injection systems. The feedback provided for the closed loop system control comes via monitoring the exhaust gas composition, such that corrections in the mixtures fuel content can be made. The monitoring is accomplished with an oxygen or lambda sensor (see Figure 4). The sensor is placed in the exhaust tract where it communicates with the exhaust gas flow from all cylinders. These sensors are solid-state devices, which provide a voltage output dependent on the oxygen concentration in the exhaust. For a detailed explanation of the operation of lambda sensors, see (6).

Fig. 36

Heated lambda sensor

1 Sensor housing, **2** Protective ceramic tube, **3** Connection cable, **4** Protective tube with slots, **5** Active sensor ceramic, **6** Contact element, **7** Protective sleeve, **8** Heater, **9** Clamp terminals for heater.

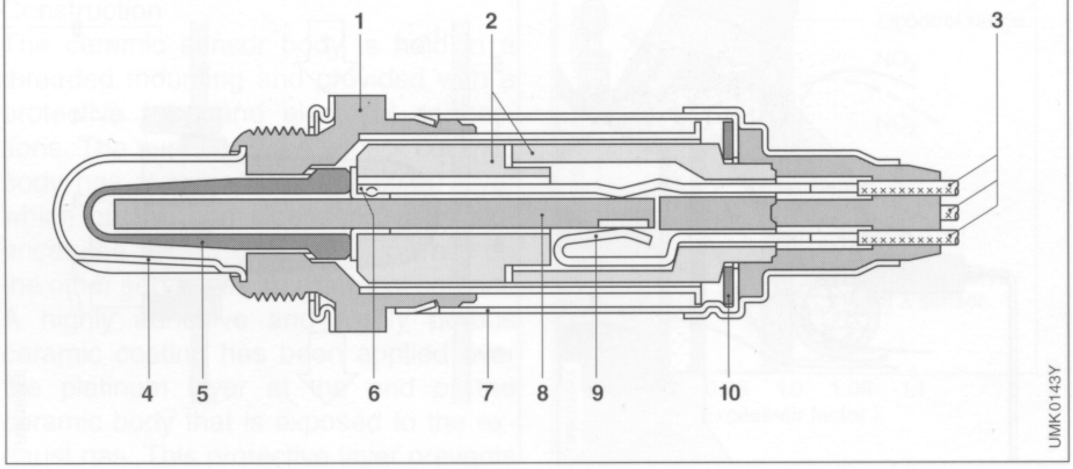
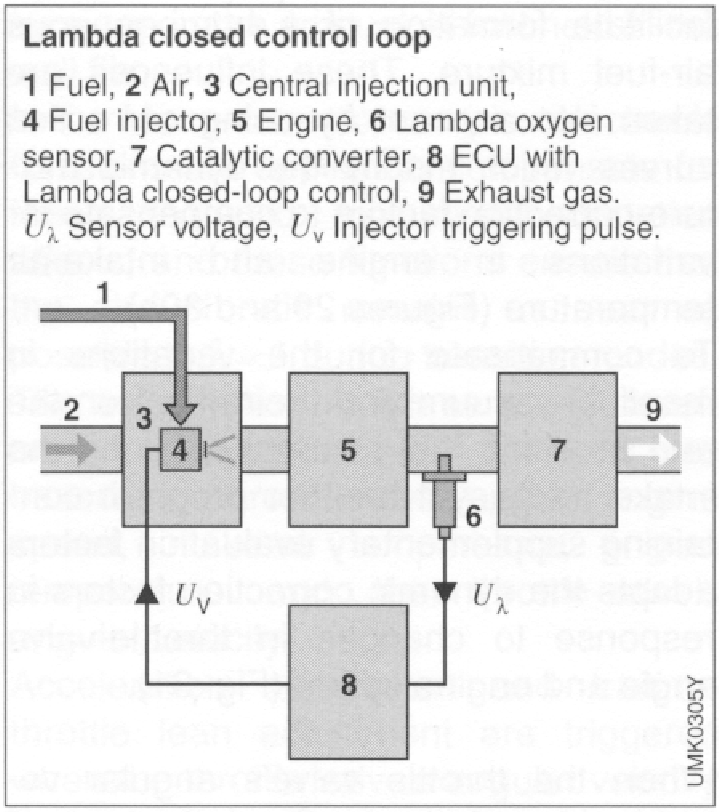


Figure 4 – Heated lambda sensor (6)

The output from the lambda sensor is fed back to the engine control unit (ECU). Using this signal, the ECU monitors the instantaneous level of oxygen content in the exhaust gas (see Figure 5). The oxygen level in the exhaust gas is a measure for the composition of the air-fuel mixture combusted by the engine. If this mixture deviates from lambda = 1, the sensor output voltage changes abruptly and is evaluated by the ECU. A high sensor output voltage indicates a mixture that is richer than stoichiometric, and the ECU instructs a reduction in the fuel injection duration to reduce the quantity of fuel injected per engine cycle. Conversely, a low sensor output voltage indicates a lean mixture, so the ECU instructs an increase in the fuel injection duration to increase to fuel quantity. A lambda correction value is applied to the injection durations to adjust the fuel metering.


Lambda closed control loop

1 Fuel, **2** Air, **3** Central injection unit, **4** Fuel injector, **5** Engine, **6** Lambda oxygen sensor, **7** Catalytic converter, **8** ECU with Lambda closed-loop control, **9** Exhaust gas. U_λ Sensor voltage, U_V Injector triggering pulse.

Fig. 32

Figure 5 - Schematic of closed loop fuelling control (6)

3.2.2.1 Lambda Correction

A lambda correction factor is determined and applied to adjust the fuel injection duration. This correction factor is determined via monitoring the switching of the oxygen sensor (as the air/fuel ratio goes from lean to rich of stoichiometric condition, or vice versa). This is shown in Figure 6. The complexities in the control algorithms for determining this lambda correction factor are beyond the scope of this report, however, an introduction can be found in (6).

This control system generally has limits on the correction factors that can be applied to the base fuel injection duration. This range of authority of the controller will vary from system to system, but would typically be limited to +/- 5 to 20% adjustment. It is necessary to limit the authority of the closed loop control to avoid gross over fuelling and under fuelling which could occur if there was some other system failure which either reduced or increased the oxygen level in the exhaust (eg large air leak in the intake system, failed regulator in the fuel system). However, systems will age, be run under different environmental conditions or even run with an oxygenated fuel such as an ethanal blend. These conditions will produce an offset to the oxygen level in the exhaust which should be compensated for without relying solely on the lambda correction factor. This separate type of control is common to most automotive control systems, and is often referred to as “adaptation”.

Fig. 33

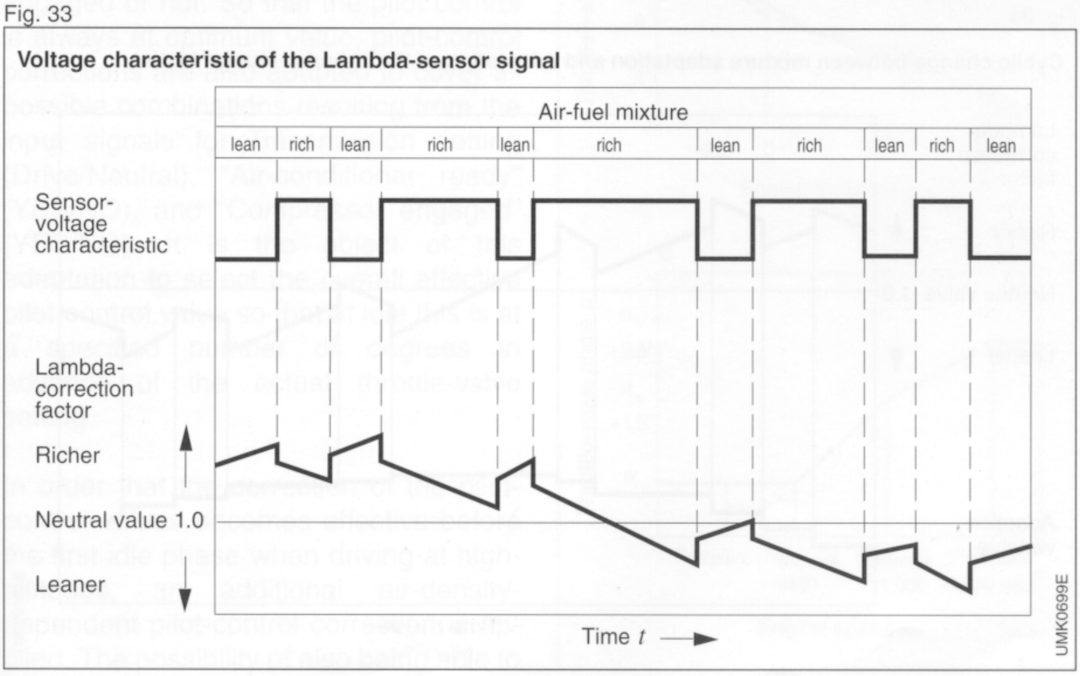


Figure 6 - Lambda correction during closed loop control operation (6)

3.2.2.2 Mixture Adaptation

Part of the control strategy for electronic fuel injection systems is mixture adaptation. This function provides separate, individual mixture adjustment for specific engine-defined operating environments. Mixture adaptation is in addition and complementary to the lambda correction factor from the oxygen sensor feedback. The Bosch “Mono-Jetronic” (6) system is designed to compensate for three variables:

1. Influences due to air density changes (altitude)
2. Vacuum leakage
3. Deviations in fuel injector response

As these variables affect different parts of the engine operating map, the mixture adaptation correction map may be divided into different regions. An example of a possible three regions is as follows:

1. complete engine map: changes which effect the complete engine map, for example altitude changes and fuel variation
2. low airflow rates – as leakage has the largest effect at low airflow rates (such as idle), an adaptation value is applied to these regions only.
3. fuel injection duration correction – the injected fuel quantity is particularly sensitive at low injection durations. These small fuel quantities are sensitive to changes in the fuel injector performance (eg. turn-on times).

In closed-loop stoichiometric control, by definition, the target (or control value) of the mixture is $\lambda = 1$. A lambda correction value is applied to the fuel injection duration to achieve the desired control value of $\lambda = 1$. For mixture adaptation, these lambda correction values are evaluated using a weighting factor before being added to the adaptation variable. Typically, the adaptation variable is adjusted in fixed increments, with the size of the increments being proportional to the current lambda correction factor (6). The increment of the mixture adaptation value then provides compensation for the mixture correction factor. This effect is shown graphically in Figure 7.

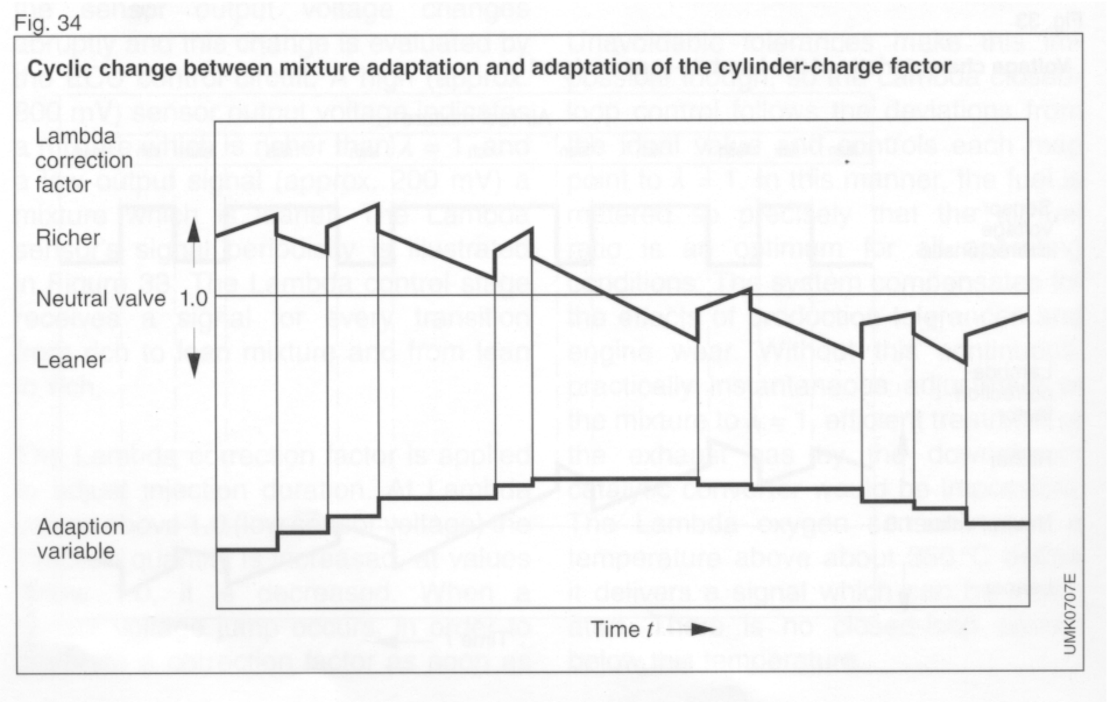


Figure 7 - Mixture adaptation incrementation and effect on lambda correction factor (6)

Commonly, the adaptation will take the form of short term and long-term adaptation. Short-term adaptation would occur during the immediate operation of the vehicle, i.e. if an ethanol blend fuel had been added the fuel delivery would be offset to compensate. Long-term adaptation is designed to compensate for the change in system components with time. This adaptation is based on taking some proportion of the short-term adaptation over a period of time. The periodicity of the adaptation value updates is both engine condition and control system dependent, and can range from milli-seconds to minutes. Both the short term and long-term adaptation will have a limit on the authority they can offset the fuelling. The limit of this authority will vary from system to system, and would typically be in the range of +/- 10 to 25%. In the event that the system could not compensate due to the limited authority of the controller, the engine management system would revert to open loop control.

3.2.2.3 Ethanol Addition

The addition of an oxygenate to a fuel effectively results in enleanment of the fuel/air mixture when no compensation is applied. For closed loop TWC systems, the mixture needs to be maintained near to stoichiometric air/fuel ratio (λ = 1) to achieve the high catalyst efficiencies required to meet legislated emissions levels. Figure 8 shows the effect on the stoichiometric air/fuel ratio with the addition of ethanol to gasoline, as well as the band within which the air/fuel ratio needs to be controlled to maintain high TWC conversion efficiencies. Also shown in this figure is the amount of fuel injection duration compensation required (incorporating the change in density of the fuel as ethanol is added) which would need to be provided by the control system to maintain stoichiometric operation of the engine. For a 10% by volume ethanol blend this corresponds to 3.3%, while for 20% ethanol, approximately 7% increase in fuel injection duration would be required.

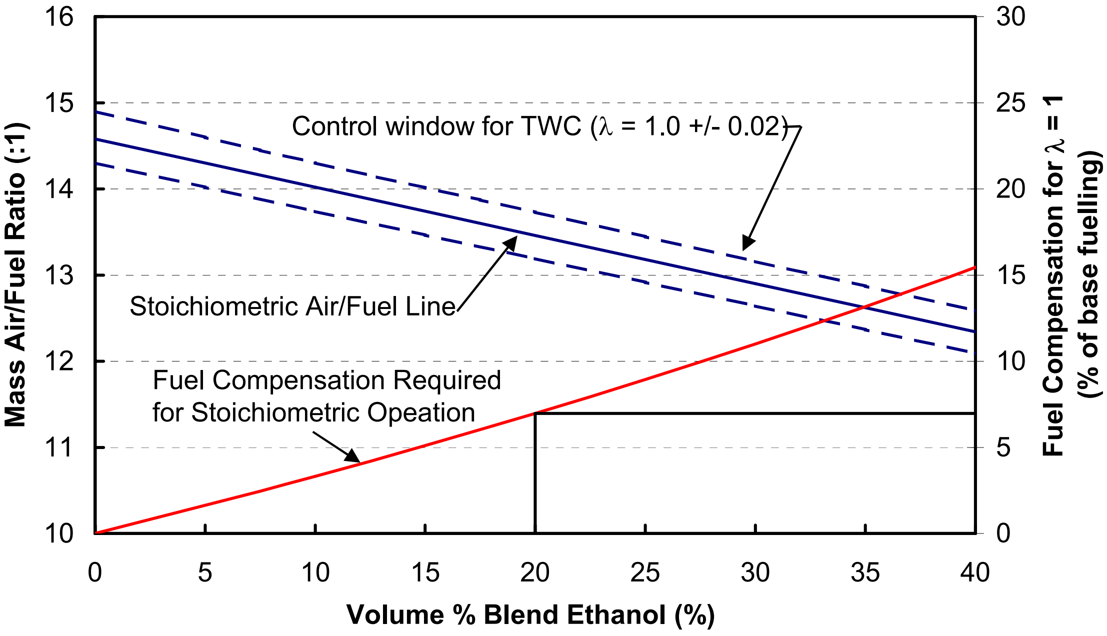


Figure 8 - Air/fuel ratio required for TWC operation with ethanol blended fuels

The closed loop controller with lambda correction and mixture adaptation must provide this increase in fuel injection duration to maintain λ = 1 operation. Figure 9 shows schematically how the controller would typically compensate for a change in the fuel properties due to addition of 20% by volume ethanol to gasoline.

As shown in Figure 9, the lambda correction value and subsequently, the mixture adaptation value are updated due to the ethanol addition to the fuel. The range of authority of the lambda correction value and the mixture adaptation value need to be sufficient to compensate for this 7% increase in fuel injection duration. The range indicated on the diagram is thought to be typical. This is not to say that there are not engine management systems in the Australian vehicle fleet which have fuel systems which can adapt to greater changes in lambda. However, with the adoption of onboard diagnostics (ADR79/01) the trend is for adaptation limits to be reduced, as the necessity for diagnosing system errors/failures becomes a requirement.

The application of the revised adaptation value to other areas of the engine-operating map would then typically occur. The extent to which this adaptation value is applied will vary between different control systems.

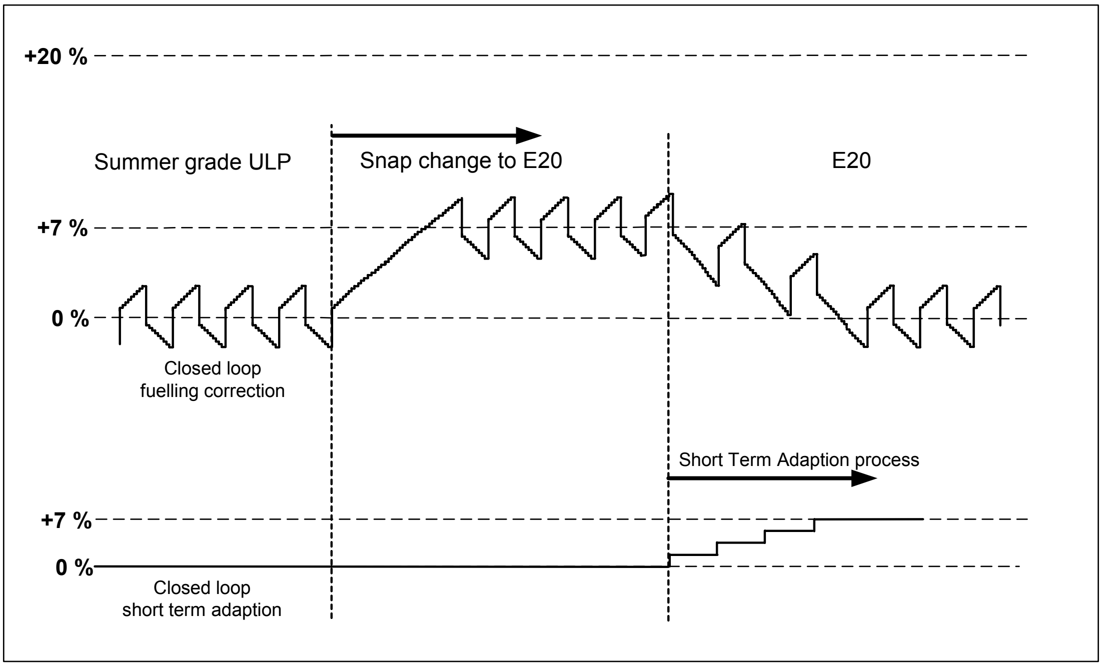


Figure 9 - Closed loop controller operation with a change to 20% ethanol gasoline blend

3.2.2.4 Open Loop Operation for Closed Loop Systems

Closed loop control systems for operation with TWC aftertreatment systems are also operated in open loop control mode under certain engine operating conditions. These include:

- Full load engine operation (often referred to as power enrichment)
- Engine starting and warm-up
- Trailing throttle

As the engine is not operated at $\lambda = 1$ in these conditions, the closed loop controller, using feedback from the oxygen sensor, is no longer operational. Therefore, during open loop operation, there is no lambda correction applied to the fuel injection durations. Typically, however, some form of mixture adaptation values are applied to areas of open loop operation depending on the control system. For correct mixture strength to be obtained during open-loop operation, the adaptation values applied to the fuel injection durations need to be suitable for the current operation. This will generally be satisfied (depending on authority etc) when the vehicle has had sufficient time to adapt to the environment in which it is running. To put this in perspective, when a vehicle has been operated for a sufficient time on high ethanol content fuel, mixture adaptation values will be incremented (as determined from the closed loop control operation areas) and applied to the engine map in areas that are operated in open loop. The mixture adaptation will then be appropriate for this fuel specification, and the open loop operation should not suffer from enleanment due to the oxygenated fuel. However, if a “snap” change occurs and the vehicle, which was operated on standard gasoline, is now operated on a high content ethanol blend fuel, the adaptation values will no longer be valid for the fuel used. This will have the largest effect on the open loop areas, which rely solely on mixture adaptation and not the lambda correction with closed loop control. Because of this, the vehicle operation (including driveability and emissions) may be very different depending on whether the vehicle has run for a period on the oxygenated fuel, or whether there is a snap change in fuel. To assess this possibility, the program of work undertaken by Orbital Engine Company will include both long-term operation and snap changes between gasoline and ethanol blends.

3.3 Vehicle Exhaust Emissions

The emissions produced by the combustion of fuel in internal combustion engines for passenger vehicles can be divided into three main areas. These are:

- Legislated (regulated) noxious emissions
- Greenhouse gas and other toxic emissions
- Carbon dioxide (CO_2) emissions (also a greenhouse gas emission).

The emissions of CO_2 and vehicle fuel consumption are partly linked, so these will be covered in a separate section (see section 3.4).

Changes in the fuel composition can change the combustion characteristics, and can therefore have significant effects on these emissions. The amount of change is dependent on how changes in fuel properties affect the operation of the engine, which is mainly linked to the fuel system operating principals, specifics of the control system design, and the design (if any) of the aftertreatment system.

3.3.1 Legislated Noxious Emissions (HC, CO, NOx)

One of the most important variables in emissions production in homogeneous charge spark ignition engines is the mixture strength, represented by either equivalence ratio or relative air/fuel ratio (λ). Figure 10 shows the effect of equivalence ratio on engine-out exhaust gas composition (31). These are the exhaust gas emissions prior to any aftertreatment of the exhaust gas by catalysts etc. Homogeneous charge, spark ignition engines need to be operated at or near stoichiometric conditions to ensure smooth and reliable combustion. Figure 10 shows how the HC and CO emissions reduce with enleanment of the mixture (equivalence ratio is reduced; lambda is increased), until there is a sudden rise in HC emissions. This rise in HC emissions is due to the mixture becoming too lean to support reliable ignition and combustion, and erratic and incomplete combustion results.

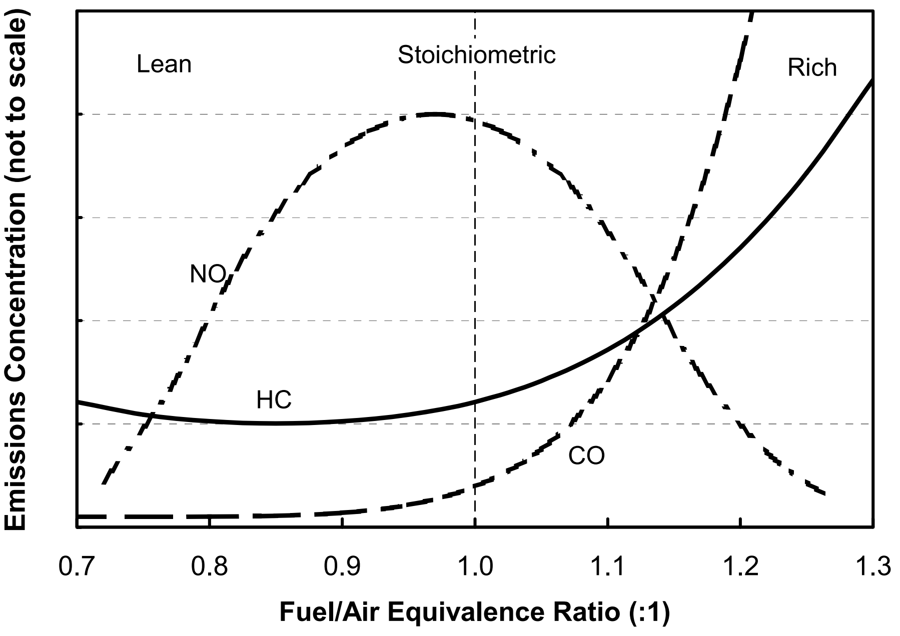


Figure 10 - Variation of HC, CO and NO concentration in SI engine with equivalence ratio (31)

As the ethanol blend is increased, if there is no adjustment of the fuel system to account for the change in fuel properties, the equivalence ratio is reduced as described in section 3.1. This would typically be the case for open loop systems, where there would be a change of approximately 0.07 in lambda going from gasoline to a 20% ethanol blend. Since the emissions effects versus equivalence ratio are very non-linear and do not monotonically increase or decrease with equivalence ratio (except for CO emissions), it is difficult to predict what the resulting effect on vehicle emissions will be with the change. As CO emissions reduce monotonically with reduced equivalence ratio, the CO emissions from vehicles equipped with open loop fuel systems reduce as the ethanol content in the fuel is increased (3,12).

For a fuel system which is designed to operate predominantly stoichiometric or richer than stoichiometric (lambda less than 1.0), an increase in ethanol content to 20% will result in lower HC emissions and higher NOx emissions when there is no closed loop control of the mixture strength. Figure 11 shows results from Birrell (3) of the exhaust concentration of HC and NOx emissions from an engine operating with gasoline and a 15% blend of ethanol with gasoline. The engine was operated with two different calibrations with the ethanol blended fuel; one with no change to the fuel delivery system (open loop), and another with fuel compensation to achieve the same equivalence ratio as per the gasoline only engine operation. This figure clearly shows how the NOx emissions are increased and the HC emissions reduced for the ethanol blend fuel with the unmodified calibration. When the equivalence ratio is restored (as would be the case for a closed loop fuel metering system), the NOx and HC emissions are virtually unchanged by the addition of ethanol. The author explains the small difference in HC measurements reported as possibly due to lower sensitivity of the measurement device (flame ionisation detectors) for ethanol.

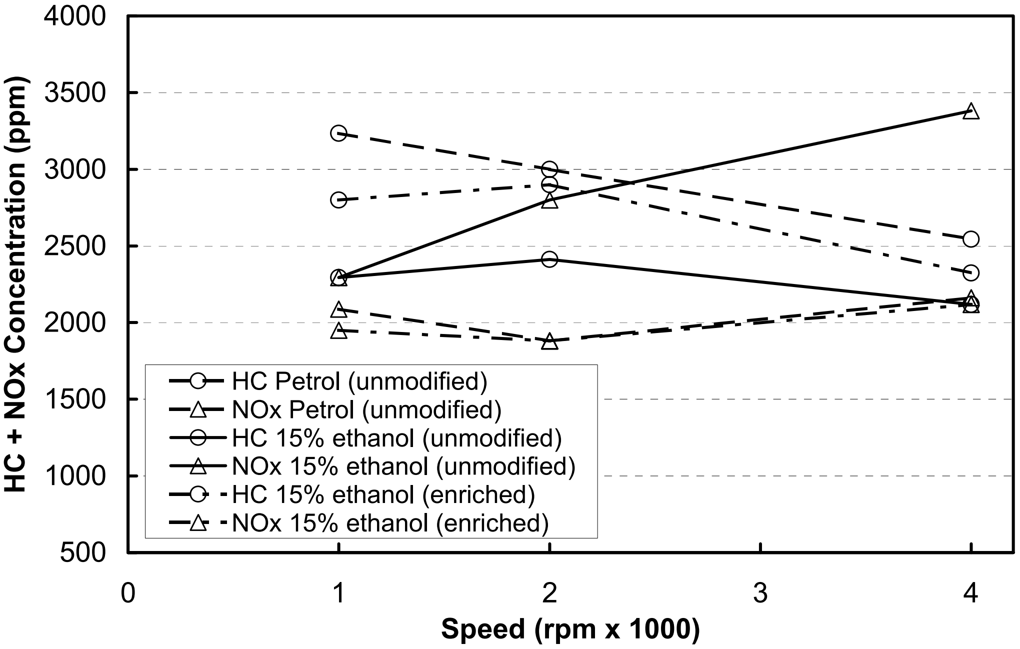


Figure 11 - HC and NOx emissions for 15% blend of ethanol with premium grade petrol, compared to petrol alone (3).

The same trends in noxious emissions have also been reported by Furey & Jackson (9). Exhaust emissions of a pre-1980 vehicle fitted a 2.5L engine were measured over the Federal Test Procedure (FTP) 75 drive cycle with gasoline-ethanol blends (by volume) of 0, 5, 10 and 20%. The vehicle was fitted with the production fuel system (open loop carburettor), which was not adjusted between fuels. The results from these tests are summarised in Figure 12. A clear trend of reduced HC and CO emissions and increased NOx emissions were observed as the ethanol concentration in the fuel increased from 0 to 20%. The standard vehicle was noted to operate at air/fuel ratios significantly richer than stoichiometric, with an average air/fuel ratio running on gasoline of approximately 12.2:1 over the FTP cycle. This equates to an equivalence ratio, when operated on gasoline only fuel, of approximately 1.2.

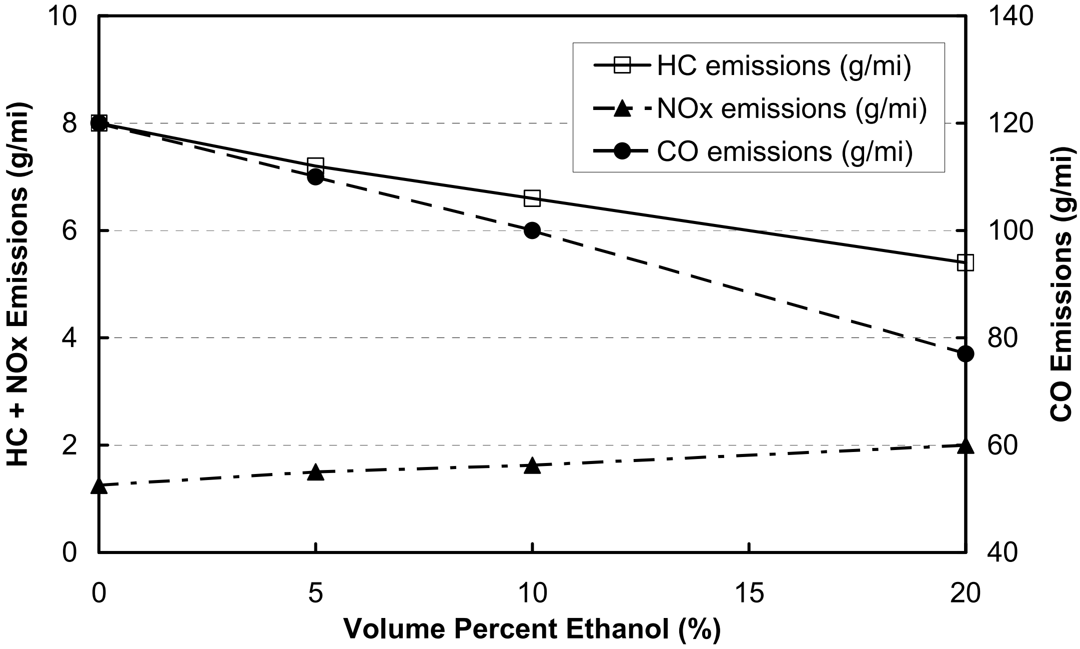


Figure 12 - Vehicle exhaust emissions of FTP drive cycle (9).

For leaner base conditions, the trend could be the opposite, with HC emissions increasing and NOx emissions reducing as the ethanol content of the fuel is increased. Testing performed by CSR Chemicals Pty Ltd. showed that the response of NOx emissions varied considerably to the addition of 15% ethanol in the fuel, with the average over 25 vehicles showing an increase of only 1% (3). To illustrate the differences that can be experienced with the addition of ethanol, a substantial NOx reduction was reported by Brinkman et al (7) with the addition of 10% ethanol to gasoline. For a pre-1980 vehicle using a production carburettor tested on the US FTP 75 drive cycle, it was found that the NOx emissions were reduced by approximately 20% while the HC emissions remained virtually unchanged when compared with the same vehicle tested with standard gasoline. On examination of the vehicle calibration, it is shown that the engine typically operated at lean air/fuel ratios (equivalence ratio less than 1.0) when running on gasoline only. The further enleanment from the addition of ethanol results in a reduction in NOx rather than an increase, as is the case when the enleanment occurs from stoichiometric air/fuel ratios. In summary, for open loop fuel systems, there is a clear trend for reduction in CO emissions. For the other legislated noxious emissions (NOx and HC emissions) the trend is highly dependent on the base vehicle engine calibration and driving conditions.

For closed loop systems, where the equivalence ratio is maintained in normal driving conditions, the effect on noxious emissions from a change in oxygen content in the fuel is minimised so long as the controller is able to maintain the desired equivalence ratio. As discussed in section 3.2.2, the ability of the controller to maintain the equivalence ratio is dependent on the actual control system for the vehicle. For ethanol blends up to 20%, it is thought that most control systems should be able to adapt sufficiently, provided there are no other high demands on the adaptation other than the change in fuel properties. For systems which experience significant drift over time which need to be compensated for by the closed loop controller, the additive effect may lead to the controller not having the range of authority required to maintain the desired equivalence ratio for the lifetime of the vehicle.

Guerrieri at al (5) report on six production vehicles, which were tested with gasoline only and 9 other different gasoline/ethanol blends, ranging from 10 to 40% by volume ethanol. The six vehicles were all 1990 model year or later, and all were equipped with electronic fuel injection technology. The vehicles were tested over the FTP drive cycle and the emissions were compared. Significant vehicle operation was performed prior to each recorded drive cycle emissions result each time the fuel was changed. The type of preconditioning performed should result in the controller adapting to the new fuel properties prior to the recorded emissions results from the drive cycle testing. No information on vehicle age (accumulated mileage) is provided, and no effect on emissions durability with the addition of ethanol to the fuel was established as part of this work. Table 2 shows the baseline results of emissions for the average of the six vehicles over the FTP drive cycle.

Parameter	Mean	Standard Deviation
THC (grams/mile)	0.191	0.076
CO (grams/mile)	2.011	1.32
NOx (grams/mile)	0.447	0.183
CO_2 (grams/mile)	405.6	33.81

Table 2- Emissions results with base fuel (5).

Vehicle results were averaged for each of the different fuel blends compared to the baseline vehicle result with gasoline only. These results are shown in Figure 13.

The results show that there is clear trend of reducing total HC emissions (which includes methane and ethane) and CO emissions with increasing ethanol content. From the results for the average of all the vehicles, there is shown to be an increase in tailpipe NOx emissions for fuels with 12 to 17% ethanol addition. Below 12% ethanol, the NOx emissions are virtually unchanged from the base level. From 17% to 30% ethanol, there is almost a constant increase in NOx emissions levels of near 30% compared to the base result. Above 30% ethanol content, there is a strong increasing trend of NOx emissions with the addition of further ethanol. This may represent the percentage above which the majority of vehicles have run out of authority for the closed loop compensation.

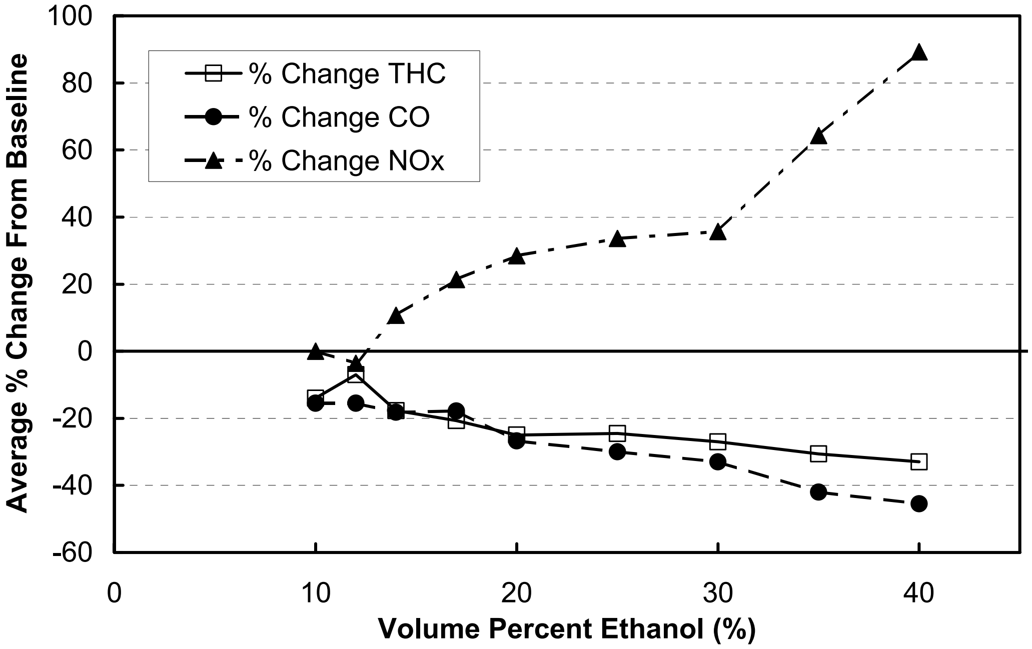


Figure 13 - Average percent change in vehicle emissions from base levels (5).

Table 3 summarises the effect on emissions of 10% and 20% ethanol addition to the base gasoline.

	Average Change from Base	
Exhaust Emission	10% Ethanol	20% Ethanol
THC Emissions	- 14%	- 25%
CO Emissions	- 16%	- 27%
NOx Emissions	0%	+ 29%

Table 3 - Emissions comparison of 10 and 20% by volume ethanol content

Comparing the results between a 10% and 20% ethanol addition, the emissions of HC and CO are both reduced by approximately 11% for the higher ethanol percentage. The NOx emissions are seen to increase by approximately 30% with a 20% ethanol blend, compared to no increase for a 10% ethanol blend when both are compared against the base vehicle results. The increase with the 20% ethanol blend represents an absolute increase in tailpipe NOx emissions of approximately 0.13 grams/mile. As this data is averaged over 6 vehicles, it is not possible to interpret from the results if this average increase of 30% is representative of each of the individual vehicles, or if only a smaller number out of the sample are contributing to this change. This is probably more likely to be the case, as individual vehicles may run out of closed loop authority before all vehicles encounter this effect.

Guerrieri et al (5) conclude that these changes in the emissions are consistent with a enleanment of the combustion process as the ethanol content is increased. As previously discussed, the addition of ethanol to the gasoline caused enleanment of the mixture for the same mass air/fuel ratio. For closed loop systems, the engine fuel management system will endeavour to correct this and compensate to adjust the mixture back to stoichiometry in order to achieve high (three-way) catalyst efficiencies. However, there are system limits for the closed loop fuel management control strategies, and once these are reached, the system is unable to compensate further. As well, the feedback compensation is not perfect even within the limits of the controller, and the resulting effect is increasing enleanment as the ethanol content is increased (5). Within this study, there was no measurement or determination of the extent of the closed loop compensation limits for each of the vehicles. Other issues which were identified as requiring more investigations for the use of high ethanol content is fuels were:

- the impact on long term tailpipe emissions
- changes in altitude and ambient conditions (pressure and temperature)
- effect on evaporative emissions.

Mooney et al (4) investigated the emissions impact with high blend ethanol (0,20,30,40 and 50% by volume) on a vehicle equipped with a 2.1 litre engine, a closed loop control system and TWC. The vehicle had accumulated less than 300 miles at the start of the test matrix, and testing was performed on the United States FTP drive cycle.

The FTP emissions results are summarised in Figure 14. The CO emissions showed the trend of continuing reduction with increased ethanol content. The effect on HC emissions with increasing ethanol blend was found to be a little more complex. With 10% ethanol blend, the HC emissions were seen to increase compared to the base, gasoline only, result. On examination of the individual bag results, it appears that the majority of this increase is due to HC increase during phase 3 of the FTP cycle. This corresponds with the hot transient part of the cycle. Between 30 to 40% ethanol content, the HC emissions are equal to or less than the base value. At greater than 40% ethanol, the HC emissions again start to increase. The authors note that results for the HC emissions did not follow the expected trend with increased ethanol content, and attribute this to vehicle driveability issues with the ethanol addition, which included hesitation and poor driveability during heavy accelerations.

For 0 to 30% ethanol content, the NOx emissions were found to be a little variable, with no clear trend set until the ethanol content was increased above 30% by volume. With 10% ethanol, the NOx emissions were identical to the baseline. With 20% ethanol addition, the NOx emissions were increased by approximately 30% compared to the baseline, while the result with 30% ethanol show a reduction in NOx emissions of approximately 30%. Above 30% ethanol, the NOx emissions increased dramatically. Mooney et al (4) comment that the control system is probably periodically reaching the limits of its compensation control range. During dynamic driving with more the 30% ethanol it is likely that the closed loop system cannot always maintain a stoichiometric air/fuel ratio to maintain maximum conversion efficiency of the TWC. This dramatic increase in tailpipe NOx emissions when operating with ethanol blends above 30% is in agreement with the finding from Guerrieri et al (5) and is consistent with the closed controller running out of authority.

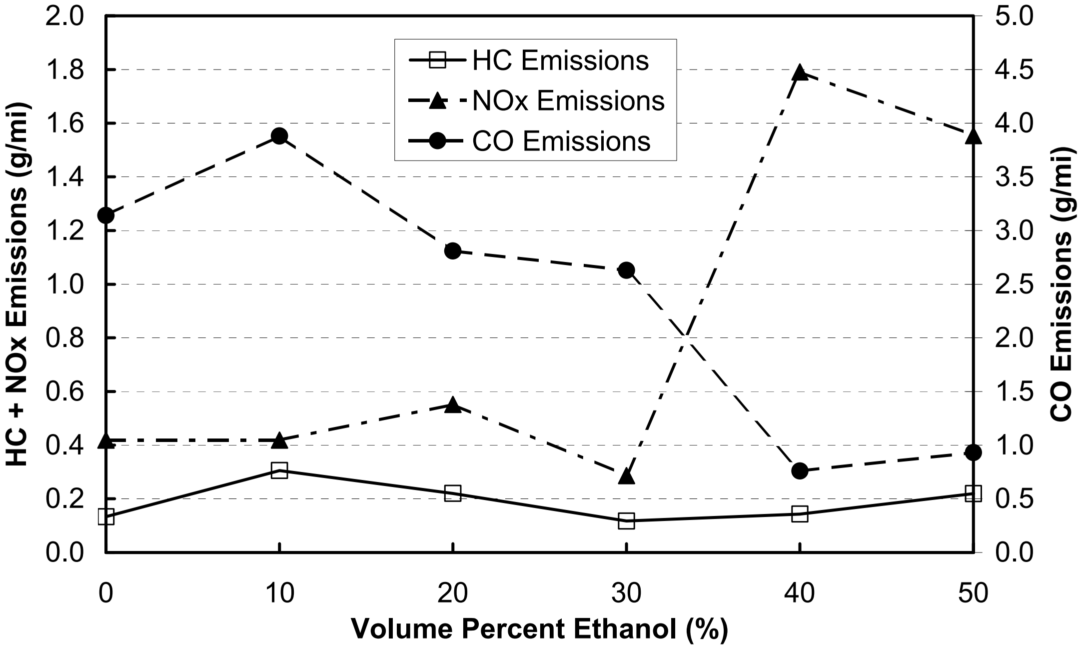


Figure 14 - 1975 FTP vehicle tailpipe emissions as a function of ethanol blend content (4).

Generally, for modern vehicles with closed loop fuel delivery systems and TWC aftertreatement systems, the addition of up to 20% ethanol results in a reduction in CO emissions, a small reduction in HC emissions, and an increase in NOx emissions. The increase in NOx emissions is of the order of 30% over the gasoline only baseline. The absolute magnitude of these increases is approximately 0.13 grams/mile (0.08 grams/km). To put this in perspective, the current ADR37/01 requires the NOx emissions to be below 1.0 g/mile (or 0.61 grams/km), and therefore this increase represents approximately 13% of the total standard. For future emissions standards, however, the limitation on NOx emissions will be significantly reduced. Although not directly comparable (due to differences in drive cycles etc), the new ADR 79/01 has a limit of 0.15 grams/km, and therefore an increase of 0.08 g/km in NOx emissions represents approximately 50% of the total limit.

3.3.2 Greenhouse Gas and Other Unregulated Toxic Emissions

The previous section focused on the effects of high ethanol addition on the legislated (or regulated) tailpipe emissions of HC, CO and NOx. Clearly this not the complete picture from an environmental perspective. The emissions from passenger vehicles contain many other substances which contribute to greenhouse gases, as well as other toxic emissions.

The most significant greenhouse gases (apart from CO_2 emissions) to be considered are:

- Methane (CH_4)
- Nitrous Oxide (N_2O)

As well, the other emissions which should be considered to ascertain the impact of ethanol blended fuels are:

- Aldehydes, including Acetaldehyde, Formaldehyde, Propionaldehyde and Acrolein
- Benzene
- Ethylbenzene
- 1,3 Butadiene
- Acrolein
- Hexane
- Toluene
- Xylene
- Fine particulate mass

3.3.2.1 Nitrous Oxide (N_2O)

Nitrous Oxide is a contributing gas to the greenhouse effect. N_2O has been given a rating of approximately 200:1 relative to the mass-equivalent global warming impacts compared with CO_2 (12). The effects on nitrous oxide emissions from modern vehicles with blends of ethanol greater than 10% are not well documented or reported in the literature. Results have been reported for a 10% blend of ethanol and gasoline by Warner-Selph & Harvey (13). In this study, five vehicles were tested over the FTP cycle. The vehicles were selected to represent the range of technologies typically in the market place. This included one vehicle each fitting into the following categories:

1. Pre 1975, carburetted, non-catalyst
2. 1975 to 1978, oxidation catalyst, air pump
3. 1980 to 1983, 3-way catalyst, closed loop carburettor, air pump
4. 1983 to 1990, 3-way catalyst, throttle body fuel injection, no air injection
5. 1983 to 1990, 3-way catalyst, port (multi-point) fuel injection, no air injection.

The results show that for all five vehicles, there was no statistically significant difference in N_2O emissions between the base gasoline only fuel and the 10% ethanol gasoline blend.

3.3.2.2 Methane (CH_4)

CH_4 has been reported as having a mass-equivalent global warming impact of approximately 20:1 compared with CO_2. Again, there is little reported data on the effects of high concentration ethanol blended fuels in the literature. Although not reported directly, Guerrieri et al (5) reported both organic matter hydrocarbon emissions (OMHCE) and total hydrocarbon emissions (THC) which includes ethane and methane. As the testing was performed in 1995 over the FTP, it is assumed that the OMHCE referred to in the paper is actually OMNMHCE (Organic Material Non-Methane Hydrocarbon Equivalent), which would be used for measurements against the emissions regulations. As reported in section 3.3.1, the THC emissions were shown to reduce as the ethanol content increased up to 40% by volume. When compared to the trend of the OMHCE (which is assumed to not include ethane and methane), the reduction in THC emissions is larger as a percentage when compared to the reduction in OMHCE alone. This would indicate that as the ethanol content is increased, the ethane and methane emissions are equivalent to, or slightly reduced compared to the base gasoline fuel.

3.3.2.3 Aldehydes

Birrell (3) measured the aldehyde emissions on an open loop control engine fuelled with gasoline and a blend of gasoline and 15% ethanol. The total aldehyde exhaust concentration was seen to increase for all conditions (minimum load and maximum load) irrespective of air/fuel ratio. This same trend was reported by Furey and Jackson (9), where a linear increase in aldehyde emissions were observed as the ethanol content was increased up to 20% by volume.

The above studies did not separate the aldehydes into different species. The aldehydes most reported are formaldehyde and acetaldehyde. No information was found in the literature survey on the effects of high ethanol blended fuels on emissions of Propionaldehyde and Acrolein (also known as acrylic aldehyde or acrylaldehyde). The general consensus is the emissions of formaldehyde will be little effected by changes in the ethanol content in the fuel (5,12). The study performed by Guerrieri et al (5) on six 1990 or later model vehicles showed that for the Formaldehyde emissions remained essentially constant for ethanol contents between 0 to 30% when blended with gasoline. Above 30% ethanol content, the Formaldehyde emissions increased gradually, showing a trend of approximately a 10% increase for each 5% increase in ethanol content above 30%.

This same study found the effect of ethanol content to be more pronounced on the acetaldehyde emissions. The data presented showed that acetaldehyde increased to approximately 200% over the baseline with a 20% ethanol blend. Acetaldehyde is considered particularly important. Acetaldehyde reacts with NOx in the atmospheric photochemical system, and produces peroxyacetyl nitrate (PAN), which is a phytotoxicant and mutagen. This effect has been confirmed by measurements in Brazil, where increased levels of acetaldehyde and PAN have been recorded since ethanol and ethanol blends has been used as motor fuels (12).

Warner-Selph & Harvey (13) performed a study which included five test vehicles that covered the range of emissions control technology, from carburetted, non-catalytic aftertreatment systems to port fuel injection with three-way catalysts. Testing was performed over the FTP using a baseline (aromatic enriched to 35.5% aromatics) gasoline only fuel and a blend with 10% ethanol. The results indicated a statistically significant increase in acetaldehyde emissions for four of the five vehicles. The average increase over the five vehicles was greater than 100%, with vehicles with and without catalytic aftertreatment systems showing a similar increase. It should be noted that the vehicles fitted with electronic fuel injection systems and TWC aftertreatment systems showed an order of magnitude lower absolute acetaldehyde emissions level when compared with earlier model year vehicles without these emissions control systems. There was no data for ethanol blends greater than 10% in this testing. Changes in formaldehyde emissions were found to be not statistically higher or lower when using the 10% ethanol blend fuel compared with the baseline fuel. This is consistent with the findings of Guerrieri et al (5).

3.3.2.4 BETX

The reported effects on exhaust emissions of BTEX (Benzene, Toluene, Ethyl benzene and Xylene) of high ethanol content blended fuels (above 10% ethanol) is limited, especially for modern vehicles with electronic closed loop fuel delivery systems with TWC aftertreatment systems. As this group of emissions is largely the by-product of combusted or un-combusted gasoline, there is general consensus that as the ethanol content is increased, the BTEX emissions are reduced (12, 26). Warner-Selph & Harvey (13) reported significant reductions in Benzene, Toluene and Xylene for a 10% ethanol blend when compared to the base gasoline only fuel results. Testing with five vehicles (each with different emissions control technology ranging from carburettor with no aftertreatment to multi-point fuel injection with TWC) over FTP cycles showed approximately a 20 to 40% reduction in Benzene, a 50 to 60% reduction in Toluene, and 40 to 60% reduction in Xylene.

3.3.2.5 1,3 Butadiene

Black (12) states that 1,3-butadiene should be reduced as ethanol content is increased. This is in agreement with the EPA’s Ethanol Special Report (USEPA (1993) EPA 420-R-93-005), which reports an expected substantial reduction in 1,3-butadiene emissions (21). The study by Warner-Selph & Harvey (13) with five vehicles, using various emissions control technologies, showed that for all five vehicles there was no statistically significant difference in the emissions of 1,3 Butadiene between the base gasoline fuel and a blend containing 10% ethanol.

3.3.2.6 Particulate Emissions

The particulate emissions of homogeneous charge, spark ignited internal combustion engines are normally very low. On review of the effect on particulate mass emissions, the general consensus is that there will be little change in particulates for increasing ethanol content in the fuel (21).

3.4 Fuel Economy and CO_2 emissions

For a given hydrocarbon based fuel, the emissions of carbon dioxide (CO_2) are inversely proportional to the vehicle fuel economy (or directly proportional to the vehicle fuel consumption). When the composition of the fuel changes, this relationship no longer holds. A reduction in volumetric fuel economy (eg mile per gallon [mpg]), as is expected as the ethanol content increases in a gasoline based fuel, does not mean the CO_2 emissions will also increase.

3.4.1 Carbon Dioxide Emissions

The predominant greenhouse gas that affects transport is CO_2. Guerrieri et al (5) reports on the effects on CO_2 emissions over the US FTP drive cycle for ethanol blended fuels up to 40% by volume. In total, six vehicles of model year 1990 or later, were tested with the different ethanol content fuels. The study found that for small additions of ethanol (from 10 % to 17% ethanol content by volume) there was a small average increase in CO_2 emissions of approximately less than 0.5%. At a 20% ethanol blend level, the CO_2 emissions were found to be the same as the base (gasoline only) fuel. Above 25% ethanol blend content, the CO_2 emissions were reduce by approximately 1.5%. The average trend of the small increase in CO_2 for the lower ethanol content blends was qualified in the report with reference to five out of the six vehicles all showing a statistically significant reduction in CO_2 emissions as the ethanol content was increased from 0 up to 40% by volume. This indicates that on the whole, it is expected that tailpipe CO_2 emissions should decrease as the amount of ethanol increases up to 40%.

When compared to other reports on the effect on greenhouse gas emissions from ethanol and ethanol/gasoline blended fuels, there is general agreement that the vehicle tailpipe emissions of greenhouse contributing gases would be slightly to dramatically reduced, depending on the level of ethanol in the fuel (18,21). This would suggest that ethanol blends could deliver a greenhouse gas benefit, however both references site the substantial differences in CO_2 emissions from the production methods of ethanol, which can dominate any reductions in the tailpipe emissions of CO_2. Beer et al (21) shows that if ethanol is produced from ethylene, a fossil fuel, then an increase in greenhouse emissions will occur when compared to gasoline. The study shows that for a very high ethanol content fuel (E85), there could be the potential for a 40 to 50% reduction in CO_2 equivalent emissions. This large reduction is applicable when ethanol is produced from wheat or molasses. However, the same fuel could result in a 60% increase in CO_2 equivalent emissions, when considering the full fuel cycle emissions, if the ethanol is produced from ethylene. This clearly demonstrates how the source of the ethanol dominates the greenhouse gas outcome. Both Beer et al (21) and Duncan (18) conclude that the difference in embodied greenhouse gas emissions from gasoline and a 10% ethanol blend with gasoline are slight.

3.4.2 Fuel economy

Fuel economy theoretically reduces when oxygenates are blended with gasoline due to the lower energy content of the oxygenate. This reduction in fuel economy, due to the reduction in energy content, may be offset somewhat in older vehicles due to the enleanment of the fuel/air mixture when there is no closed loop fuel control (16). Kortum et al (11) showed fuel economy reduction was directly proportional to the reduction in energy content of the blended fuel when ethanol as added. This was limited to blends of up to 10% ethanol, which show a reduction in fuel economy of approximately 3% when compared to gasoline only fuel. For higher concentrations, for example 20% ethanol, it is expected that this linear trend will continue, especially for modern vehicles with closed loop fuel delivery control systems. Therefore, a fuel economy reduction of approximately 6% would be expected while the closed loop controller was able to maintain stoichiometric combustion conditions within its range of adaptation authority. Table 4 shows the theoretical reduction in fuel economy (on a fuel volume basis) based on the prediction for fuel energy loss as the ethanol content is increased.

Ethanol Content (%)	Energy from ethanol (Btu/gal)	Energy from gasoline (Btu/gal)	Energy of 1 gal of Blend (Btu/gal)	FE change c.f gasoline (%)
5.7	4,332	102,787	107,119	-1.7
7.7	5,852	100,607	106,459	-2.3
10.0	7,600	98,100	105,700	-3.0
20.0	15,200	87,200	102,400	-6.1

Table 4 - Theoretically expected effect of ethanol addition to gasoline on fuel energy

Table 5 shows the results from the testing performed by Guerrieri et al (5) over the US FTP drive cycle using different ethanol/gasoline blend fuels. This testing was performed with six 1990 model year or later vehicles, all featuring closed-loop fuelling control.

Ethanol Percentage	Average Heat of Combustion (BTU/Gallon)	Change in Heat of Combustion (%)	Average Fuel Economy (mpg)	Change in Fuel Economy (%)
0	115,650	-	22.00	-
10	112,080	-3.10	21.25	-3.41
12	111,130	-3.91	20.92	-4.90
14	110,500	-4.45	20.90	-5.00
17	109,660	-5.18	20.63	-6.23
20	108,550	-6.14	20.48	-6.91
25	106,510	-7.90	20.13	-8.50
30	104,860	-9.33	20.00	-9.09
35	102,750	-11.15	19.57	-11.05
40	104,270		15.64	

Table 5 - Heat of combustion and Fuel economy for various Ethanol blends (5)

These results show how the reduction in fuel economy is within 1% of the reduction in heat of combustion as the ethanol content is increased from 0 to 35%. The average reduction in vehicle fuel economy for 20% ethanol is seen to be approximately 7% when compared with gasoline only. This 7% reduction in fuel economy is thought to be typical of what the Australian consumer is likely to experience if a 20% ethanol blend is used. This magnitude of reduction is likely to be noticeable.

3.5 Evaporative Emissions

Evaporative losses from vehicles can occur from several different sources. The major sources from a fuel system perspective are breathing losses from the fuel tank, carburettor bowl (for older vehicles) and fuel system component permeation.

As fuel evaporates in the fuel tank, hydrocarbons can be discharged into the atmosphere. To control these fuel vapours from the fuel tank, vehicles are equipped with an evaporative emissions control system whereby the fuel tank is connected to a carbon canister (Figure 15). This canister absorbs fuel from the fuel tank, and then as the engine draws in air through the canister, allows the stored fuel to desorb in the air stream to be induced into the engine and subsequently burned as part of the normal combustion process.

Fig. 9

Evaporative-emissions control system

1 Line from fuel tank to carbon canister, **2** Carbon canister, **3** Fresh air, **4** Canister-purge valve, **5** Line to intake manifold, **6** Throttle valve.
p_S Intake-manifold pressure, p_u Atmospheric pressure, Δp Difference between intake-manifold pressure and atmospheric pressure.

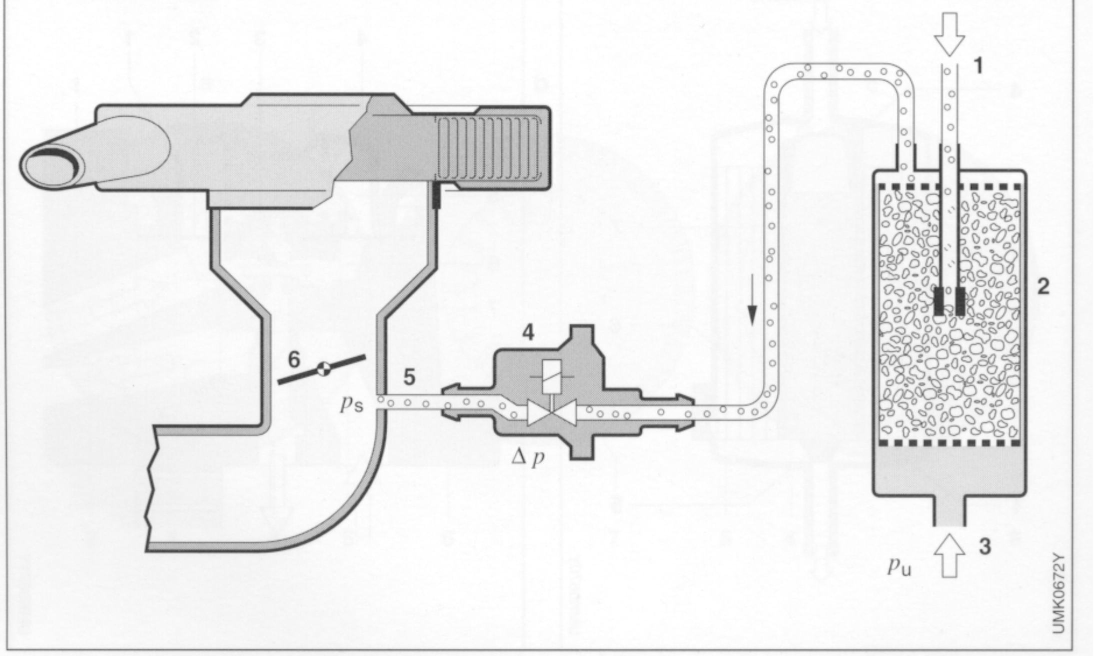


Figure 15 - Evaporative emissions control system (6)

Permeation is the migration of hydrocarbons through any materials used in the fuel system. The common areas of permeation are seals, flexible hoses and other fuel system components such as fuel tanks that are made of plastic, nylon etc.

3.5.1 Ethanol Blended Fuel Volatility

Evaporative emissions are influenced by the volatility of the fuel. An increase in RVP (Reid Vapour Pressure – a measure of the fuel volatility) due to the presence of oxygenates such as ethanol, will give a corresponding increase in evaporative emissions (16). When small amounts of ethanol are added to gasoline, the vapour pressure of the mixture is greater than the vapour pressure of either the gasoline or alcohol alone. The molecules of pure alcohol are strongly hydrogen-bonded, but with small amounts of alcohol in a non-polar material (i.e. gasoline) the hydrogen bonding is much less extensive and the alcohol molecules behave in a manner more in keeping with their low molecular weight. Thus the alcohol becomes more volatile. For automotive fuels, this volatility is defined as the RVP measured at 37.8 deg C.

When ethanol is added to gasoline, the RVP of the blend is increased by about 7kPa for 5 to 10% by volume ethanol content. The RVP gradually declines when the ethanol content exceeds 10%, and at between 30 to 45% becomes equivalent to the base gasoline volatility.

Figure 16 shows RVP of the fuel for different ethanol blend content. The RVP only drops consistently below the petrol RVP with blends of ethanol greater than 30%.

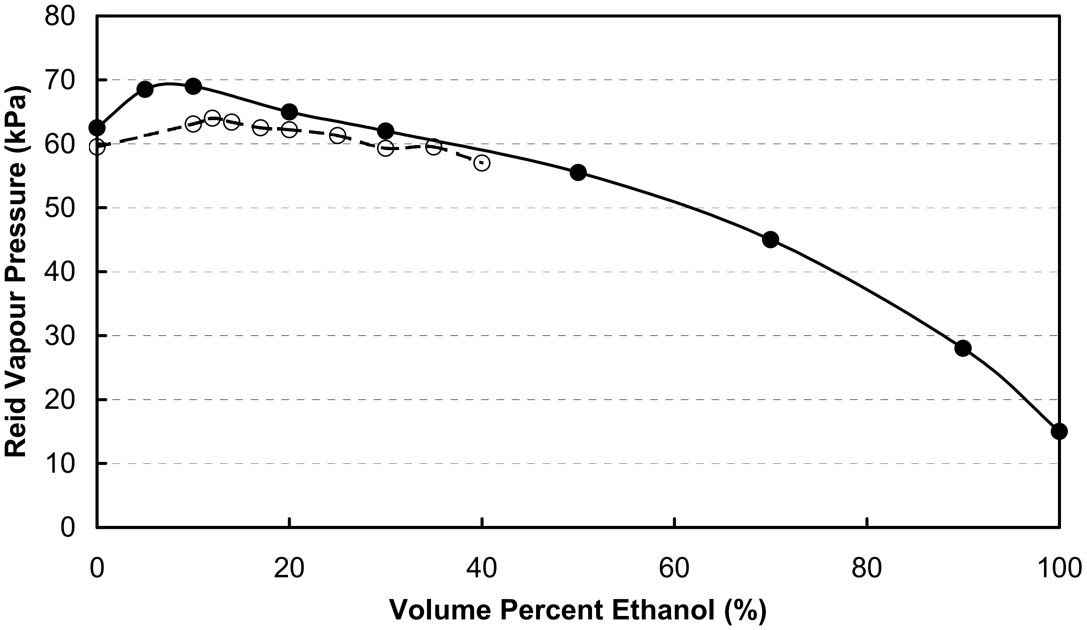


Figure 16 - Reid Vapour Pressure with High Blend Ethanol; solid line – Furey & Jackson (9), dashed line – Guerrieri et al (5).

There is also considerable difference in the distillation curves for ethanol blended fuel. Figure 17 shows the distillation temperatures T10, T50 and T90 as the ethanol blend content in increased. There is a significant difference in the T50 distillation temperature for a 10% ethanol blend compared to 20%. This is the temperature at which 50% of the fuel will be vaporised.

The net affect of the potential for a higher RVP and lower distillation temperature is for the vehicle evaporative system to have to store more vapour and/or allow it leak into the atmosphere. This is compounded by the fact that carbon canister used to store vapour before being emitted into the engine appear to lose working capacity when ethanol blends are introduced. Alcohols are preferentially stored by the canister, and not as effectively purged, so the canister efficiency may be reduced. This may lead to an effective reduction in the working capacity of the canister, which can then lead to increased evaporative emissions (9,18)

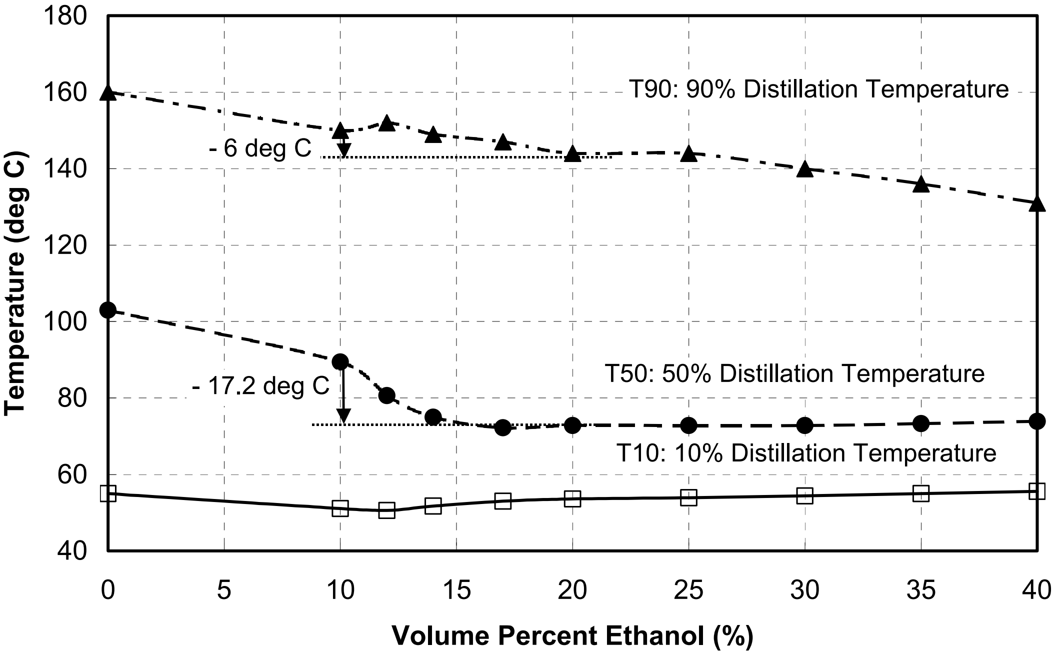


Figure 17 - The distillation temperatures with high blending ethanol (5)

3.5.2 Evaporative Emissions Legislative Testing

Evaporative emissions testing typically consist of a diurnal test and a hot soak test. Advanced evaporative emissions requirements also include a running loss test. A brief description of these tests is:

1. Diurnal Test – this test is preformed with the vehicle after an extended soak period. The temperature of the fuel tank / vehicle is cycled and the airborne hydrocarbon emissions are measured.
2. Hot Soak Test – after pre-conditioning the vehicle by set driving cycles, the vehicle is allowed to hot soak for 1 hour and the airborne hydrocarbon emissions are measured.
3. Running Loss Test – during vehicle operation, a point source sampling system collects and measures fuel vapours from predetermined locations where emissions would likely occur.

The actual durations, temperatures and pre-conditioning for these tests vary for different emissions regulations.

Furey & Jackson (9) performed evaporative emissions measurements on a 1974 model year vehicle, which had no evaporative emissions controls. The vehicle was tested with three fuels; gasoline, a 10% ethanol in gasoline blend (without RVP adjustment), and 10% ethanol in gasoline blend with adjusted volatility to match the gasoline only fuel. The results show that the diurnal evaporative emissions were slightly reduced with both the ethanol blend fuels. The hot soak emissions, however, were substantially higher (approximately double the gasoline values) for the ethanol blend fuels. The total evaporative emissions measured (diurnal + hot soak) increased slightly for the two ethanol blend fuels.

The distillation curve presented in section 4.1.1.2 (Figure 18) helps to explain these findings. The diurnal test performed heated the fuel tank to 29 deg C (84.2 deg F). At this temperature, the percentage of gasoline evaporated is similar or slightly higher than that of a 10% ethanol blend. This finding is similar to Reddy (8), who shows that the vapour pressure of an oxygenated fuel drops more rapidly with a reduction in temperature, ie from 37.8 deg C (where the RVP of the fuel is specified) to 22.8 deg C. Therefore, the oxygenated fuel can have a lower vapour pressure than gasoline at the lower temperatures experienced during the diurnal test, even though the RVP at 37.8 deg C is the same or higher for the oxygenated fuel.

For the hot soak test, the carburettor float bowl temperature has a strong influence on the evaporative emissions (9). These temperatures are substantially higher than the diurnal testing, and in the region where the percentage of evaporated fuel is higher for the ethanol blend fuel compared with gasoline only.

Warner-Selph & Harvey (13) measured evaporative emissions for five test vehicles to represent a wide range of emissions control equipment (see section 3.3.2). Testing was conducted with gasoline and a blend of 10% by volume ethanol blended with gasoline. The ethanol blend fuel had a RVP of approximately 1 psi (7 kPa) higher than the gasoline only fuel. Evaporative emissions were measured for diurnal and hot soak conditions, including total HC emissions and some unregulated evaporative emissions. The results showed a general increase in hot soak total HC emissions of the order of 40% (from 12 to 50%) for the ethanol blend fuel, with the diurnal emissions not showing any clear trend. Overall, the evaporative emissions were increased by approximately 30% on average with the 10% ethanol blend fuel. Unregulated evaporative emissions of MTBE, ethanol and benzene were also measured using the US Federal Test Procedure. The results showed that MTBE and benzene were not statistically higher or lower for the 10% by volume ethanol blend compared with the base gasoline fuel. Evaporative emissions of ethanol were increased for the ethanol blend fuel (as would be expected) by one to two orders of magnitude. It should be noted that some ethanol was measured for the evaporative emissions of the base gasoline fuel. This may indicate a small quantity of ethanol was present in the base fuel, but no details are supplied in the report.

The literature survey conducted found no evaporative emissions data for high ethanol blend fuels (> 10% ethanol content). Based on the distillation curves and RVP values for a 20% ethanol blend compared to a 10% ethanol blend, it is expected that the vapour generation during a diurnal test would be less for the 20% ethanol blend compared to the 10% blend. As the study shows little effect of 10% ethanol compared to gasoline only for the diurnal test, it is expected that for this part of the evaporative emissions testing, a higher ethanol content should not have an adverse effect. However, the hot soak evaporative emissions are expected to be higher for the higher ethanol content blends due to the increased vapour generation at the higher temperatures.

3.5.3 Permeation

Permeation is the migration of hydrocarbons through any of materials used in the fuel system. Metals are thought to have zero permeation. Elastomers, used for hoses and seals, are permeable as are relatively rigid materials like polyethylene and nylon. Plastic fuel tanks, nylon fuel hoses and nylon carbon canister bodies all have some degree of permeation (10).

Published permeation rates show a wide range of values for various materials used in vehicles and these rates were increased by blending ethanol. For a 10% by volume ethanol blend, the permeation rate of NBR (Nitrile Butadiene Rubber) increased by 54%, and Nylon 12 increased by 336% against the base fuel (10). Actual mini-SHED tests showed that permeation would increase by a factor of ten with the addition of 10% ethanol by volume to gasoline. This equates to an increase of 1.4 grams per day additional to the original evaporative emissions total (10). It is expected that this rate will be further increased by the addition of 20% ethanol.

3.6 Discussion

Ethanol addition to gasoline increases the oxygen content in the fuel. This effectively changes the ideal or stoichiometric air to fuel ratio of the fuel. For fuel systems without feedback systems (open-loop), this leads to enleanment of the air/fuel mixture. This enleanment can have a significant effect on the emissions generated by the combustion process. As the ethanol content in the fuel increases, the enleanment increases which leads to a reduction in CO emissions. HC and NOx emissions are difficult to predict, and the effect of 20% by volume of ethanol on vehicles fitted with these older fuel systems, will differ depending on the engine calibration in standard form.

For closed loop control fuel systems with TWC aftertreatment systems, the trend is for reductions in tailpipe CO emissions and similar or reduced HC emissions for ethanol blends of 20% by volume when compared to gasoline-only fuels. The reported data indicates an average increase of approximately 30% in NOx emissions levels for a 20% ethanol content compared to gasoline only. This increase equates to approximately 0.13 grams/mile, which represents approximately 13% of the current Australian emissions legislated value for tailpipe NOx emissions. The legislated target for NOx emissions will decrease significantly with the introduction of the new Australian Design Rule (ADR) 79/01, where a similar increase in NOx emissions will represent approximately 50% of the target. Authors of the relevant studies cite closed-loop controller accuracy and adaptation authority as the likely reasons for the increased NOx emissions recorded. No actual recordings of the function of the controllers have been reported. The literature survey did not find any information on the high-mileage emissions degradation effects with high ethanol blend fuels.

Both open-loop and closed-loop systems show a trend of increasing aldehydes with ethanol addition to the fuel. This increase is predominately due to increases in acetaldehyde, with formaldehyde emissions remaining relatively constant for ethanol blends up to 30% by volume. The acetaldehyde emissions are increased by more than 100% for ethanol blends of greater than 10% by volume. For other unregulated emissions, only data relating to a 10% ethanol blend content was found. This data shows emissions of other toxic and noxious emissions to be similar or reduced with the addition of ethanol to gasoline fuels.

CO_2 emissions from vehicles are likely to be slightly reduced for a 20% ethanol content. The potential for a greenhouse gas emissions benefit from this reduction needs to be evaluated while considering the full fuel life cycle, as the production of ethanol can be energy (and CO2) demanding, and threatens to dominate any reductions in CO_2 produced at the vehicle. Vehicle fuel economy will reduce by approximately 7% with the addition of 20% ethanol by volume.

It is highly likely that the evaporative emissions from a 20% by volume ethanol blend will increase over a gasoline-only fuel. This is based on the hot soak emissions measurements reported in the literature. Currently, the evaporative emissions test for ADR 37/01 (19) has a hot soak test and a diurnal test. The introduction of ADR 79/01 (Euro3 equivalent) adds a “real time diurnal test” which is highly likely to further increase the evaporative emission with a 20% ethanol blend due to the combination of a “hot soak test” and “24 hours heat build” (20).

4 VEHICLE OPERABILITY ISSUES

Vehicle operability covers a significant range of subjects; some of these are covered in the following sections. Vehicle driveability issues are covered in relation to cold start as well as hot and cold weather driveability. The effects of ethanol blends on fuel quality are discussed in terms of how the vehicle responds to the changes in the behaviour of the fuel when ethanol is added. The performance of the vehicle is next and the analysis is formed in terms of the effect that the addition of ethanol has on the octane rating of the base gasoline. The factor of enleanment or "lean shift" is also discussed in terms of the driveability and performance of the vehicle.

Firstly however, fuel quality is covered in terms of the impacts ethanol will have when added to the base gasoline. It is assumed that the ethanol is mixed with normal volatility pump fuel, with unmodified distillation characteristics or make-up.

4.1 Fuel Quality.

Fuel quality can have dramatic effects on vehicle performance under certain conditions. Two significant issues of fuel quality are those of anti-knock and volatility. Knocking can limit the amount of engine power available and give rise to catastrophic engine damage, while changes to the volatility of the fuel can have significant effects on the driveability of the vehicle, (16,17).

4.1.1 Volatility

Fuel volatility can be described by vapour pressure and the distillation curve, each of which is important in understanding what is required from the fuel in terms of satisfying the driveability requirements as well as the effects the addition of ethanol can impose on the driveability of the vehicle.

4.1.1.1 Reid Vapour Pressure

The addition of ethanol to gasoline results in an increase in the vapour pressure. Guibet (22) states that increases in the Reid Vapour Pressure (RVP) of 6 – 8 kPa can be expected with ethanol additions of only 3% to base gasoline with normal volatility. This increase in RVP is confirmed by Owen & Coley (16). The RVP is a measure of the vapour pressure of a liquid as measured by the ASTM D 323 procedure and is commonly applied to automotive fuels. It is usually used as a test to define the volatility of the fuel.

Table 6 shows the change effect of an addition of 10% and 20% ethanol on the RVP of the base gasoline fuel using data from Owen & Coley.

Volume % Ethanol added	RVP (kPa)
0	62
10	67.3
20	69

Table 6 - Increase in RVP with ethanol addition

4.1.1.2 Distillation curve.

Three regions of the distillation curve are important for the behaviour of a fuel in an engine (16,27). The front end, defined by Owen and Coley (16) as the compounds in the fuel having boiling points up to approximately 70°C, is the first to be distilled over. This controls the ease of starting and the likelihood of hot weather problems such as vapour lock occurring.

The mid-range effectively controls the way the vehicle drives in cold weather. In particular it has a significant bearing on the warm-up behaviour of the engine in terms of the time taken for the engine to warm-up. Two further important factors are the operational readiness of the hot engine and the behaviour of the hot engine under acceleration. The percentage of the fuel compounds that vaporise at 100°C determines the engines behaviour under the operational conditions just described (16,27,30). The mid point of the gasoline's distillation curve has been used as the principle cold weather driveability control parameter (30).

The final region contains all the heavier compounds. These compounds have a high heat content and are important in improving fuel economy when the engine is fully warmed up. A further requirement on this region is that at a temperature of 180°C, the volume evaporated should be of a significant level so as not to cause dilution of the engine oil through these compounds finding their way into the engine crankcase by passing the piston rings as liquids,(16).

The ASTM D86 Distillation test is also used to define the gasoline volatility, producing a curve similar to that of the base gasoline as shown in Figure 18, (16).

Figure 18 shows the effect of oxygenates on the distillation curve for Indolene HO III fuel with a RVP of 62 kPa (9 psi) from Owen and Coley (16). Considering only the distillation curve for the gasoline, it can be seen that displacing the distillation curve downwards the gasoline will become more volatile and the RVP will increase. Should the distillation curve be displaced upward, the gasoline becomes less volatile with a correspondingly decreasing RVP.

Following (16), it should be noted that weather conditions, particularly ambient temperature, influence the choice of volatility required for satisfactory vehicle operation. Altitude has a small effect due to the atmospheric pressure influencing the rate of evaporation of the fuel. Vehicles themselves vary significantly in terms of the way they respond to fuel volatility, some being very tolerant while others exhibit severe driveability problems if the fuel volatility is not matched closely to the prevailing weather conditions. The vehicle design aspect which is the most important factor in this respect is the proximity of the fuel system to hot engine parts.

Clearly, setting the volatility specifications of the fuel is a compromise that is influenced by the prevailing weather conditions, geographical location and the characteristics of the vehicle population, (16).

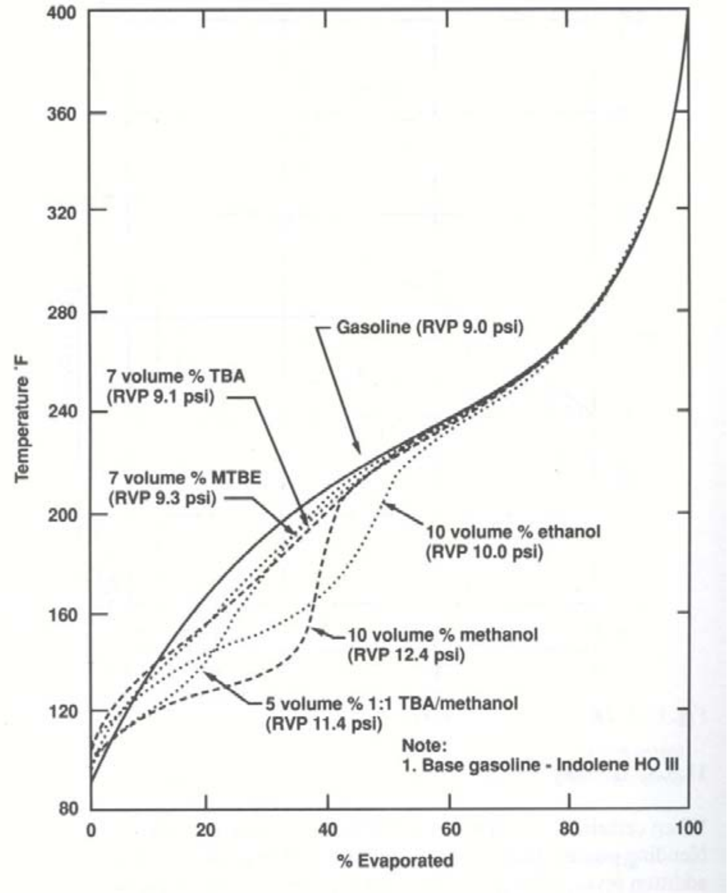


Figure 18 - Effect of Oxygenates on Distillation (16)

Figure 18 shows the effect of adding 10% by volume of ethanol to the base gasoline. Clearly, this results in the front end to the mid region of the curve being heavily distorted in terms of significantly increasing the volatility of the fuel in these regions. Wagner et al. (17) also shows a similar curve to Figure 18 for a 10% ethanol blend and explains that the addition of ethanol into gasoline has significant and curious effects on the volatility of the blend. Further, data from Guerrieri et al. (5) presented in section 3.5.1 (Figure 17) shows that the effect of 20% ethanol addition to gasoline continues to increase the volatility of the blend with further decreases of both the T50 and T90 distillation temperatures. The T50 term is used to denote the temperature at which 50% by volume of the fuel will evaporate, and therefore T90 is the temperature at which 90% of the fuel will evaporate. The reductions seen in T50 and T90 between 10 and 20% ethanol are greater than the reductions from neat gasoline to the 10% ethanol blend, demonstrating a non-linear trend. Beyond the 20% ethanol addition, the T50 distillation temperature remains relatively constant while the T90 distillation temperature continues to fall as ethanol is added up to 40% by volume. For example, the T50 for the gasoline was 103°C, for 10% ethanol the T50 was 89.4°C and for the 20% ethanol blend T50 was 72.8°C.

4.1.2 Octane Number

The Research Octane Number (RON) and the Motor Octane Number (MON) as determined by the usual ASTM procedures are used by many authors to indicate that when gasoline is blended with alcohol an increase in the fuel octane occurs over the base gasoline (3,6,16,17,1). There is however, some question as to whether the conventional octane measures of RON and MON give a reliable guide as to the on road octane performance of the fuel when alcohol is blended with gasoline (6). This question is particularly raised when ethanol is blended with gasoline (3,16), though Owen and Coley (16) also state that other work has shown satisfactory correlation between RON, MON and the road octane performance of the ethanol gasoline blend. The on road octane performance is described by the road octane number since it is obtained by testing on the road according to Owen and Coley. To carry out such fuel ratings on the road, the spark timing of the engine is adjusted to find a setting which gives trace knock for the particular fuel and driving mode, whereas when measuring octane requirements through RON and MON, the fuel quality is varied to find the octane level at which trace knock occurs.

Using methanol, which Brinkman et al. (6) suggests gives a comparable effect to that of ethanol, the authors show that the addition of methanol to the base gasoline increases the RON in an almost linear fashion in proportion to the concentration of methanol added, while the MON initially increases and then plateaus beyond approximately 15% addition of methanol by volume, Figure 19 shows this trend. Other authors, (3,17) also show the known trend of increases in RON and MON with addition of ethanol to gasoline. It should be noted that fuel sensitivity increases with the increasing margin between the RON and MON, defined as (RON – MON), by Brinkman et al. and Heywood (31), Figure 19 clearly demonstrates the increase in fuel sensitivity with increasing alcohol content of the fuel. A further trend that can be observed from the reviewed literature is the lower the octane number of the base gasoline, the higher the increase in octane number when ethanol is added. Table 7 shows this trend.

Author	Gasoline	MON	RON	% Ethanol added	MON	RON
Szwarc and Branco (26)	Regular	73	-	20%	81	-
Wagner et al. (17)	Regular	83	92	10%	85	96
Birrell (3)	Regular	-	89	18%	-	97
	Premium	-	97	15%	-	102
Mooney et al. (4)	ULP	-	92.9	30%	-	102.6

Table 7 - Effect of Ethanol Addition on Octane Number

Owen and Coley (16) report on a study where a wide range of oxygenates, including ethanol, were blended with gasoline such that the RON and MON were kept constant. The study showed that with a low level of olefins (10%) in the base gasoline, an improvement to the accelerating knock performance with addition of oxygenate over the base gasoline was found, with a reduction of octane requirement of approximately 0.5 of a point. However, the reverse was true with higher olefin levels (20%). When considering constant speed, ethanol blends gave the worst performance, increasing the octane requirement by approximately 1 point over the base gasoline. The octane requirement can, following Owen and Coley, be defined as the octane number of a reference fuel (any fuel) that gives a trace knock level in an engine on a test bed or a vehicle on the road when being driven under specified conditions. Owen and Coley suggest it is only possible to generalise on the effects of oxygenates, as with all octane related work, the actual effect is a

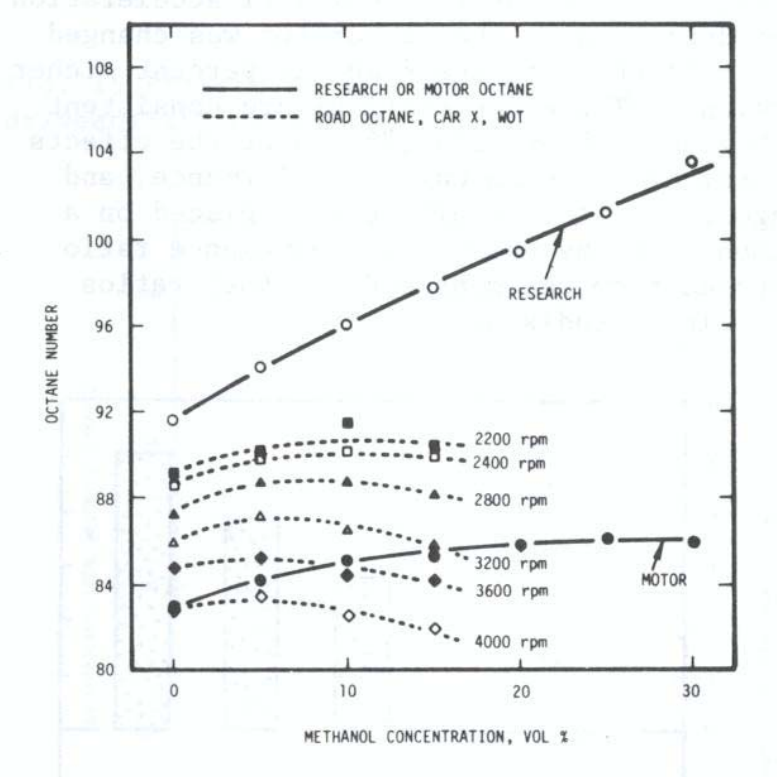


Figure 19- Effect of Methanol Addition on RON and MON (6)

function of the vehicle, the composition of the fuel and the actual test method adopted. Brinkman et al. (6) defines the maximum octane requirement as that occurring at an equivalence ratio of 1.1 corresponding with the maximum brake mean effective pressure. Either side of this equivalence ratio, the octane requirement decreases. Birrell (3) suggests that the equivalence ratio at which maximum knock sensitivity occurs is very close to 1.0 for the engine tested in his paper. Vehicles differ greatly in the way they respond to octane parameters and in the level of octane quality they require to be clear of knock. It is important for the automotive and oil industry to understand the octane requirements of vehicles under both normal and severe driving conditions so that fuels can be made available to satisfy essentially all vehicles in a given population regardless of the driving conditions, (16).

4.2 Enleanment.

The detail of why enleanment occurs in an engine when ethanol is blended with gasoline is described in section 3.1. The affects of enleanment have been reported by a number of authors in terms of the impact on the vehicle driveability, (6,16,1). Brinkman et al. (6) suggest that for carburetted vehicles, the effect of enleanment will be strongly linked to the calibration of the carburettor. If the exhaust emissions requirements for the vehicle tested have been met by a lean calibrated carburettor, further enleanment due to the ethanol blend would seriously deteriorate the driveability of the vehicle. Owen and Coley (16) also suggest this is the case. On the contrary, pre-emissions vehicles with a rich calibration may not be subject to deterioration of driveability, (6). Palmer and Lang (29) state that for a given oxygenate type, oxygenate concentration alone had no detectable effect on driveability performance, while the most important factor was reported to be volatility. The authors did not provide any indication on the calibration of the carburettor, however, based on the other literature it could be assumed the calibration was rich.

4.3 Vehicle Driveability

Essentially, the driveability of the vehicle, or driver satisfaction, is directly affected by the volatility and octane number of the fuel. These two factors are also of most importance to the refiner as controlling them is costly, (26). Owen and Coley (16) define driveability as the response of the vehicle to the throttle. A vehicle with good driveability will accelerate smoothly without stumbling or hesitating, will idle evenly and will cruise without surging. Modern vehicles have considerably improved driveability such that the typical consumer is not able to detect performance flaws to the fine level that a trained rater/driver is able, (28). However, Owen and Coley report that tests carried out in the US with both open loop and closed loop systems, poorer driveability was obtained with gasoline containing alcohol, even when the volatilities of the fuels used were matched. Arters et al. (28) suggest factors such as fuel temperature, engine temperature and the temperature of the air which mixes with the fuel directly affect fuel vaporisation. Engine cold start enrichment is also a function of temperature. These factors impact on the ability of the engine control system to maintain stoichiometry within the gas phase in the engine cylinder, thereby affecting combustion quality and ultimately, driveability.

4.3.1 Cold Start

Cold startability is highly dependant on the fuels ability to vaporise effectively at low temperatures and provide an ignitable mixture at the time of ignition. Owen and Coley (16) state that for alcohol blends, cold starting depends on the vaporisation of the gasoline front end (more volatile fractions). However, when alcohol is present, the vapour contains a greater concentration of alcohol than would be expected based on the vapour pressure of the alcohol or it’s concentration in the gasoline. Together with ethanol’s higher heat of vaporisation than for hydrocarbons, more heat is required to vaporise the blends containing them. Effectively, the mixture suffers from enleanment due to the higher concentration of alcohol. All these factors indicate cold starting difficulties on vehicles operating with alcohol blends, and test work confirms this, (16).

Brinkman et al. (6) has undertaken cold start tests and reports that in order to force the engine to idle, pumping of the accelerator pedal was required, though this was at a very low temperature of –29°C and with a 20% methanol gasoline blend. The reason for the starting problem was attributed to phase separation via inspection of the lower level of the fuel tank. The author does however state that from an engineering viewpoint, results from methanol studies could also be used to predict the behaviour of ethanol under similar circumstances.

4.3.2 Hot Weather Driveability

When gasoline vaporises prematurely in the fuel system, ie., upstream of the carburettor jets or fuel injectors, driveability problems may occur. The likelihood of the gasoline vaporising will depend on engine design, ambient temperature and pressure, driving mode and fuel volatility.

Fuel system design in terms of its proximity to hot engine components and the positioning of the fuel pump are important considerations to help control hot weather driveability problems. When fuel pumps supplying fuel pressure to carburettors or fuel injectors are situated in the fuel tank, the fuel under pressure is much less likely to vaporise. However, fuel pumps or fuel lines close to the hot engine increase the possibility of undesirable vaporisation. Ambient temperature is obviously important in causing hot weather driveability problems as is high altitude driving. This is not only due to the reduced ambient pressure, but also because it means the engine compartment is very hot due to the increased load on the engine required to negotiate the climb, (16).

Excessive front-end volatility can cause poor hot weather driveability as described by Owen and Coley (16). According to the authors this is mostly due to vapour lock arising from the increased volatility of the ethanol blend as described in section on the distillation curve, 4.1.1.2. Wagner et al. (17) also suggest that the higher RVP and lower distillation temperatures (higher volatility) make vehicles prone to vapour lock once they are warmed up. The outcome of the vapour lock problem was to promote engine stalling. Birrell (3) reported consistent hot starting problems with a 15% ethanol blend; the problem was confined to one vehicle model.

4.3.3 Cold Weather Driveability

It is well known that vehicle driveability deteriorates as the ambient temperature decreases. The driveability of the vehicle is most critical during the period it is warming up. When a single point injection or carburetted engine is cold and the ambient temperature is low, a large portion of the fuel can be present in the inlet manifold as a liquid film. It is this lack of vaporisation that gives rise, for example, to a hesitation before a burnable mixture reaches the cylinders at the start of an acceleration. The uneven idle or surging during cruise in carburettor or single point injection vehicles may be caused by maldistribution of fuel between the cylinders. This can be another reason for stumble during acceleration, (16).

Owen and Coley (16) report on a number of test programs that have been carried out to assess the influence of oxygenates on cold and moderate temperature driveability. At these low temperatures, drivers are able to readily notice a worsening performance due to the addition of oxygenates to the fuel. Increases in the time to achieve a warmed up condition are also encountered for the oxygenated fuels; the extent of the increase will depend on the vehicle design, oxygenate content, ambient temperature, fuel volatility and the test method. They also state that testing undertaken using fuels with atypical distillation characteristics show that the further the fuel distillation curve deviates from the conventional, the worse the cold weather driveability of the vehicle.

Harrison (30) states that cold weather driveability of oxygenated fuels is inferior to that of hydrocarbon fuels of the same T50. However this inferiority is attributed to the different stoichiometry and the higher latent heat of vaporisation for alcohol blended with gasoline, which are not characterised by the distillation parameters. The higher latent heat of vaporisation of alcohol/gasoline blends in the intake manifold of the engine is also presented by Wagner (17) as the reason for impairing the warm-up performance of the vehicle. Wagner suggests that to restore the gasoline like performance, intake manifold heating would be required, which cannot be done practically without vehicle redesign.

After tests undertaken by Brinkman et al. (6) were analysed, they concluded that should methanol-gasoline blends be used in vehicles with carburettors calibrated for lean engine operation, driveability would be severely deteriorated at intermediate temperatures. Further, they also conclude that adding 10% methanol to Indolene produced driveability deterioration equivalent to lowering the ambient temperature from 20°C to –7°C.

4.4 Engine Performance

There are two factors to consider with the addition of ethanol to gasoline when considering the performance of the engine at WOT.

- Increase in the RON and MON, potentially providing the engine with an increased knock limit.
- Increase in the oxygen content of the blend, changing stoichiometry by introducing enleanment.

These factors are analysed in the following section.

4.4.1 WOT Performance

Birrell (3) performed a series of tests devised to study the relationship between spark timing required for the onset of knock and two ethanol blend fuels. Four types of fuels were used and the engine was operated under wide open throttle (WOT) conditions at engine speeds of 1000, 2000 and 4000 rpm. Table 8 shows the fuels used. Fuel 1 was used as the baseline and for the three engine speeds tested, the knock limited spark timing for each of the speeds was determined and represents the datum. The knock limited spark timing at each engine speed was re-optimised for each of the other three fuels, 2,3 & 4.

Table 9 shows the approximate differences in the knock limited spark timing at each speed for the three other fuels when referenced to Fuel 1, the premium grade gasoline. It is clear from the testing and the author makes the statement that the knock resistance of the engine tested is seen to be reduced by the use of the ethanol blends with only the 1000 rpm test speed reflecting the RON increase attributed to the ethanol addition. According to Heywood (31), this behaviour is typical of fuel with high sensitivity, where the region of knock occurs at the higher engine speeds.

Fuel Type	Designation	RON
Premium Grade Gasoline	Fuel 1	97
Premium Grade Gasoline + 15% Ethanol	Fuel 2	102
Regular Grade Gasoline	Fuel 3	89
Regular Grade Gasoline + 18% Ethanol	Fuel 4	97

Table 8 - Fuels used by Birrell (3)

Engine speed (rpm)	Change in spark timing relative to Fuel 1, ° crank angle		
	Fuel 2	Fuel 3	Fuel 4
1000	+10	-15	+2
2000	+1	-14	-4
4000	-10	-4	-8

Table 9 - The variation of spark timing with fuel (3)

Within Birrell's (3) testing the question of the effect of enleanment on the knock performance of the ethanol blends was addressed. Fuels 1 & 2 were compared at the engine speed of 4000 rpm by altering the fuel delivery by adjustment of the main carburettor jet, thereby allowing testing at various equivalence ratios. The author suggests that when operating at the same equivalence ratio as the unadjusted main jet when using Fuel1, the reduction in anti knock performance of Fuel 2 was not as pronounced. The authors graph indicates the change in spark timing was approximately –9 degrees crank angle compared with –10 degrees crank angle when no adjustment to equivalence ratio was made.

The experience of Brinkman et al. (6) is similar with that reported by Birrell, though not as pronounced. Figure 19 shows the effect of adding methanol to gasoline in varying percentages from 5 to 15 on the road octane number of the fuels tested by Brinkman et al. The authors determined the road octane number by using the CRC Modified Borderline technique. It is clear from Figure 19 that after 2800 rpm, the road octane number for the alcohol blends with more then 5% alcohol was reduced below that measured for the base gasoline. Brinkman et al. also note the potential effect of enleanment; however do not specifically test to determine the enleanment effect. They do however conclude that with a 10% methanol blend, knocking would be slightly decreased.

Joseph and Grogan (13) report that there was a need to adjust the ignition timing of approximately 10 vehicles in the very significant fleet of vehicles run within their experiment. The authors offer no conclusive judgement as to whether or not the 15% ethanol blend caused the timing problems. They do however make mention of the increased octane rating of the blend over the base gasoline.

4.5 Discussion

In terms of driveability, some of the literature indicated that there would be some deterioration under various conditions related to both the design of the vehicle and the type of test undertaken on the vehicle. In terms of vehicles with lean calibrated carburettors, there are most likely to be driveability related issues under all circumstances both hot and cold weather. These driveability related issues are generally described under the headings of excessive front end volatility and enleanment.

Carburetted vehicles with a rich calibration may not suffer the driveability related problems related to enleanment, though should still be subject to those arising from the volatility changes that occur with ethanol blends including the E20 blend. It is however surprising that the ethanol blend experiment carried out by Joseph and Grogan (13) did not uncover any such issue, with the authors concluding that no significant change in performance of the automotive equipment occurred. This is in direct contrast to other findings of a similar period.

There is evidence to suggest that vehicles fitted with electronic fuel injection systems may not suffer the driveability problems described earlier. Mooney et al. (4) upon testing a closed loop fuel injected vehicle concluded that ethanol gasoline blends of up to 30% ethanol may be utilised with excellent vehicle operation. This conclusion is in contrast to the statements of Owen and Coley (16) which describe testing in the US with closed loop systems showing poorer driveability with the oxygenated fuel even though the volatilities were matched, indicating that enleanment was the likely culprit. Exactly how to explain these conflicting views is unclear, however such issues as manufacturer differences in terms of control strategy or differing emissions requirements are potential factors.

It is clear that the WOT performance of the engine tested by Birrell (3) showed an impact with the ethanol blends run in the engine. This impact was described in terms of a significant reduction in the knock limited spark timing at higher engine speeds. It is rather surprising that Birrell did not present any data related to the actual brake performance differences resulting from the ethanol gasoline blends tested when considering the significant changes in the spark timing the author applied across the speed range tested.

Brinkman et al. also showed inferior performance in terms of the road octane number of the blends tested at the higher engine speeds, however, there was no quantification of the effect. The authors in fact make a surprising conclusion that knocking would be slightly decreased. The conclusion that can be reached is that it is not clear from the available literature what the actual impact a 20% ethanol gasoline blend will have on the Australian vehicle fleet, and testing is therefore required to provide data to help determine the potential impact.

Within the testing regime Orbital has constructed to understand the impact of the 20% ethanol blend, both WOT testing and on road driveability testing is identified to capture information to understand this particular impact.

The WOT testing shall be completed on the chassis dynamometer where the time required to achieve various road speeds from standing and moving starts are measured and recorded. The actual test procedure has been adopted form the SAE standard J1491, which was followed as closely as possible. The presence or absence of audible engine knock will also be noted during these tests. Both ULP and the E20 ethanol blend fuels are to be tested to provide the comparison data for evaluation.

On road driveability testing includes the audible assessment of engine knock for various WOT acceleration conditions including launch and passing acceleration.

The current program does not include any testing to make a quantitative analysis of the behaviour of the engine under WOT conditions in terms of the brake performance of the engine relative to the knock limited spark timing of the base ULP and the E20 blend. This would require the installation of an engine into an engine dynamometer test cell and should be considered in order to provide this analysis.

Within the E20 testing program, the volatility and octane number of the fuel utilised for all testing will be managed by measuring the fuel parameters that define the fuel quality. This includes the base fuels used to which the ethanol is added. A quality procedure has also been determined ensuring that the actual ethanol blend contains very close to 20% by volume ethanol

5 ENGINE DURABILITY

Engines in vehicles produced by automotive manufacturers have been tested on and passed durability test cycles to ensure satisfactory operation of the engine over the vehicles design life. Upon passing the durability testing to the manufactures standards, the manufacturer can be relatively certain the vehicles are capable meeting their customer's expectations and warrant them accordingly. Should the vehicle be operated with fuels, oils and other fluids not meeting the manufacturers specifications, questions are then raised in relation to the vehicle being able to meet the manufacturers durability standards.

Issues related to the potential engine durability degradation have been raised, with various stakeholders having differing views, (1). The following sections review the literature related to studies undertaken to identify the potential engine durability impacts of using ethanol gasoline blends in automotive engines.

5.1 Wear on Engines

There have been studies completed on the metal to metal wear differences due to the impact of using alcohol and alcohol gasoline blends. The evidence reported by Black (12) is that ethanol blends offer less lubrication to metal parts. The same paper also reports that should long cranking periods be required to start the engine, metal to metal contact occurs due to the alcohol washing away the lubrication film. It should be noted that though it is not clear, this might be based on straight alcohol fuels. Testing reported by Owen and Coley (16) expressed some concerns as to whether the use of alcohols in fuel would increase engine wear, with the authors indicating that oxygenate additions allowing a 3.5% increase in oxygen level would not require specially formulated lubricants.

Actual measurements of top, second and oil control piston ring radial depth loss when running two 4.1 litre 6 cylinder engines, one on premium leaded gasoline and the other on a 20% ethanol blend with the premium unleaded gasoline are presented by (3). The data shows less measured wear for the 20% ethanol blend. Measurements of the crankshaft bearings and the inlet and exhaust valves for valve recession data were also made. No data was given for the crankshaft bearings, however the inlet and exhaust valves show increased recession for the 20% ethanol blend test with the exhaust valve showing severe recession for the relatively short test period of 100 hours at 4000 rpm WOT.

While Birrell (3) concluded that the engines tested demonstrated a high degree of knock while operating at WOT and high engine speed, to the extent of having the spark timing reduced by 10° crank angle at 4000 rpm in the anti-knock section of the authors paper, it was also stated that the engines at the completion of the 100 hour durability evaluation test did not present with any detectable damage upon stripping and evaluation of the engine components. Oil analyses carried out at the end of each of the tests showed higher concentrations of all wear metals and silicon for the leaded gasoline fuelled test engine.

A significantly sized fleet trial containing approximately 900 automotive units was carried out by (13) at the Du Pont Company's Savannah River Plant. The trial included a number of different ethanol blends (10%, 15% and 20%), with the vehicles covering over 10 million miles consuming 1,000,000 gallons of the various ethanol blends. Though the author's state that no controlled tests were conducted and that their experience offers no quantitative support to other ethanol blend trials, they do state that no evidence of abnormal internal engine wear on spark plugs, valves or valve seats was detected and that this experience was consistent with other gasohol users. There is no reference to the other gasohol users provided by the authors.

5.2 Deposit Formation

Intake system deposits (ISD) are the deposits discussed in any significant detail by the various authors of the literature reviewed. In particular, deposits on the back of the intake valve is referenced as the area of most concern. This concern is clear due to the intake valve and seat area presenting the flow restriction point in the intake tract of modern engines.

Intake system deposits are reported by (22,25) to be more prevalent with fuels containing alcohol. The authors (25) explain that gasoline contains two types of additive packages to control deposits. The two different additive packages are formulated to control deposits on the pintle of the fuel injector to ensure accurate fuel metering and to control the deposits on the surfaces of the intake system, particularly the intake valve, to ensure the engines charge airflow is not compromised. Their detailed testing has shown that adding 10% by volume neat ethanol to gasoline with adequate ISD additive increased intake valve deposits by more than 350%. This is not only due to the dilution effect but also due to an antagonistic effect since neat ethanol blended at 10% by volume with gasoline without ISD additive increased intake valve deposits by 37% over the gasoline base without ISD additive. Increasing the ISD additive by 50% over the normal concentration in gasoline was found necessary with 10% ethanol blends in order to achieve the same deposit control as with normal ISD additive levels in gasoline. Some of the experiences reported by (25) are confirmed by (16). Firstly that intake system deposits have been found in the intake valve area, and also includes the intake manifold area; and secondly that the deposits can be controlled with higher additive levels than would be required for gasoline only (16).

The large fleet trial carried out by (13) which did not present any quantitative data, states that no evidence was detected of any abnormal internal engine deposits and this is the experience of other gasohol users, the authors do not reference the other gasohol users.

5.3 Lubrication Issues

Evidence of the potential lubrication issues associated with alcohol gasoline blends is presented by (12) as alcohol gasoline blends allow greater metal to metal contact than straight gasoline. The author also states that ethanol gasoline blends tend to provide less lubrication to methanol gasoline blends. Test work has shown that gasoline containing methanol up to a 3.5% oxygen level does not show a perceivable increase in engine wear with commercially available lubricants. It was therefore concluded by (16) that specially formulated lubricants are not necessary up to the 3.5% oxygen level of oxygenate addition.

Start up wear occurs when liquid alcohol supplied during starting “washes” the oil film off the engine components thus increasing metal to metal contact. Should long cranking periods occur, severe metal to metal wear can occur, (12).

5.4 Discussion

With respect to the three areas of engine durability detailed above, the review of the literature gathered presents a picture of either two opposing views or not enough information. In terms of the engine wear issue; Birrell (3) tests the datum engine with leaded premium gasoline and the 20% ethanol engine with unleaded gasoline. This it self raises doubts on the wear data presented since the gasoline used for the testing is different between the two tests. Further, Birrell shows data requiring that the spark timing of the test engine during the anti-knock test must be reduced by up to 10° crank angle when operating with either 15% or 18% ethanol blends. However the author operates engines for 100 hours of durability testing at the same speed and load conditions as the anti-knock test and reports no evidence of engine damage. This is also a contradictory circumstance as should the engine while completing its 100 hour durability run have done so with a spark timing 10° crank angle more then the knock limited spark timing it is difficult to understand why there was no evidence of knock damage.

A similar situation exists for the deposit formation issue, with one detailed scientific approach presenting data showing a definite deposit problem, while a very large program of work presenting that no real deposit issue was indicated in their investigation.

As part of the E20 program, Orbital is to make accurate measurements and recordings of internal engine components before and after mileage accumulation on E20 fuel. These measurements and recordings, which have been targeted to clearly reveal a wear situation, will then be compared to determine the level of engine wear that has occurred after the 80,000km mileage. The planned driving cycle used for this mileage accumulation is representative of normal on road use and therefore includes idle, wide open throttle and part throttle conditions at various road speeds.

6 FUEL SYSTEM DURABILITY

The stable performance of the fuel system for an engine is of paramount importance to ensure the vehicle will be able to meet its intended design features including emissions regulations, driveability performance or customer satisfaction and safety requirements. The vast majority of fuel systems on vehicles sold in Australia have been designed for operation with gasoline. Should a modified fuel, not considered during the design phase of the fuel system be introduced to the fuel system, it is likely the fuel system may not perform as intended for the design life of the fuel system. The following sections present the findings of a review of the available literature on the impacts of ethanol blends on fuel systems and their components.

6.1 Corrosion of fuel system components

The mechanism by which corrosion of metallic fuel system components in fuel systems occurs when there is a presence of alcohol in the fuel is partly due to the increased water content of the fuel and partly because of the organic acids that can be present in commercial oxygenates, (16). Should the dissolved water level in the ethanol increase to the point where it can no longer remain in solution, de-mixing occurs and the chemical aggressiveness of the ethanol toward metallic materials is further increased. Galvanic corrosion, which occurs in the presence of an electric field, is also more likely as ethanol is a better conductor then gasoline, (12).

Corrosive attack of fuel system metals such as steel, zinc die-castings and aluminium has been identified by Owen and Coley (16). Protection such as nickel or tin surface treatments have been utilised to protect against the corrosive attack, (15). Further, Szwarc and Branco (26) stated that corrosion resistant materials and coatings were required for fuel systems required to operate with ethanol blends from 14 to 20%. These fuel systems were previously designed for operation with gasoline only. Corrosion of the zinc die casting in carburettor bodies was observed by Birrell (3), where the deposition of fine zinc particles occurred in the wetted areas of the carburettor. Ethanol is reported to cause corrosion problems with the carburettor, fuel pump, fuel line, fuel filter, and the fuel tank. The problem becomes critical even before the corrosive action damages the part as the particles of corrosion can plug small openings in the carburettor (15).

6.2 Perishing of fuel system components

The solvent action of alcohols and alcohol gasoline blends has been reported by a number of authors, (3,12,1). Adhesive failure where the bond between the carburettor float and float arm failed due to the solvent action of a 20% ethanol blend was reported by Birrell (3). The likelihood of elastomers to swell, soften and loose tensile strength is clearly reported. Plastics and fibre-reinforced plastic receive attention with ethanol blends causing weakening, brittle behaviour, crack and leaks. Warnings related to the potential for attack by ethanol blends on those fuel systems components manufactured from elastomers and plastic, giving consideration to materials compatibility issues and issues of serious degradation of fuel systems parts are stated, (3,4, 12,16,17,1). It is reported by Szwarc and Branco (26) that for ethanol blends ranging from 14 through to 20%, the fuel pump diaphragm material which was compatible with gasoline, was replaced by a neoprene material for ethanol compatibility reasons.

6.3 Fuel system deposits

The solvent action of ethanol gasoline blends has been introduced earlier. This action is the mechanism by which various fuel system deposits have been either “stripped out” or loosened (3,12,13) and redeposited within the fuel system causing blockages of fuel lines, filters and plugging of carburettor jets. Those deposits that have been reported as causing the blockages and plugging include gums, fuel oxidation deposits, rust deposits, resin particles from electric fuel pumps and varnishes, (3,12,13,16,1). The deposits listed are normally occurring in fuel systems using gasoline and are passive in the presence of gasoline.

The reported the blockages occurred shortly after a vehicle changed from gasoline to ethanol blends. The vehicles effected were older vehicles that had previously only operated on gasoline. In many cases frequent multiple filter and fuel line changes were required before the fuel system reached a ‘clean’ status, (3,13). The ethanol blend strengths causing the blockages were generally in the range of 10 – 20% by volume.

6.4 Phase Separation

Water of up to a concentration of 50 ppm at ambient temperatures will remain in solution with gasoline causing no fuel system related problems. Ethanol has an affinity for water and should the water content of an ethanol gasoline blend increase, phase separation or de-mixing is likely to occur. This process is temperature dependent occurring more readily at lower temperatures with lower ethanol content and therefore more readily at higher temperatures with higher ethanol content, (22). The temperatures mentioned are in the ambient temperature range. Brinkman et al. (6) in their testing reported an occurrence of phase separation with a 20% methanol blend at –29^{o}C, not a temperature readily found in Australia.

6.5 Discussion

Based on the preceding fuel system durability sections, it is clear that corrosion, perishing, swelling and deposits are significant issues. The impacts are most likely to be initially seen within the older vehicle fleet in terms of fuel line and fuel filter blockages and potentially as plugging of the fuel metering components by deposits. This is expected since age has allowed the fuel systems deposits identified earlier to build up to the ‘normal’ level.

Following the vehicle owners’ replacement or cleaning of the affected hardware, the next likely issue is perishing or swelling of the elastomeric and degradation of plastic fuel system components.

The newer vehicle fleet may well also begin to experience the problems related to the elastomeric and plastic components within their fuel systems after some time has passed. It may be that the impact could be somewhat less than for the older vehicles. This will be dependent on the specification of the materials used. Those components most likely to be affected are flexible fuel supply lines, plastic fuel tanks, plastic canister vapour purge tanks, elastomeric diaphragms in fuel pressure regulators and fuel pressure dampers. This should be tempered with the understanding that the newer vehicle fuel systems are assembled with components that are potentially produced to be compatible with up to 10% ethanol, due to global sourcing strategies, and therefore should have an element of protection against the effects of a 20% ethanol blend.

Phase separation means that the water and ethanol will separate out from the hydrocarbons in the gasoline. When this occurs in a vehicle fuel tank, the ethanol/water phase will in fact reside below the gasoline due to the lower density of the gasoline. The phase separation process will mean a mixture of alcohol and water will reside at the bottom of the vehicle fuel tank. Fuel pump pick-ups are located near the bottom of the fuel tank, and therefore fuel drawn from this area will be effectively the ethanol and water mixture. Fuel supplied to the engine under these conditions would cause a vehicle to break down immediately.

Actual damage of metal fuel system components due to the corrosive nature of the E20 blend is likely to be a longer term issue as the corrosion process is generally slow.

The potential impacts of the issues discussed can be listed as follows:

- Safety impact due to fuel leakage and fire.
- Driveability related issues.
- Exhaust gas emission issues.
- Evaporative emission issues.

Only testing of representative components along with long term durability testing with the E20 ethanol blend can provide accurate information of the possible impact.

The testing identified for the E20 program is targeted to capture the effects described above and the testing includes:

- Components compatibility tests for perishing and corrosion.
- Durability testing for perishing and corrosion.
- Fuel system tests for deposit related issues.

- Cold operability testing within which phase separation will be monitored.

7 CONCLUSIONS

A study has been conducted on the suitability of ethanol/gasoline blend fuels that contain greater than 10% (by volume) ethanol. The study has focussed on researching published data on the effect of high ethanol blend fuels for light-duty automotive vehicles on noxious and greenhouse emissions, vehicle operability and engine and fuel system durability. The available data needs to be considered in the context of the current vehicle fleet, which must operate effectively and efficiently on higher ethanol blends without the need for re-tuning/recalibration or other modification. In many cases, there is incomplete, insufficient or conflicting information available, and hence vindicates the detailed testing program, which is to be undertaken as part of tender 34/2002, is warranted.

Ethanol is an oxygenate, and as such when blended with gasoline increases the available oxygen for the combustion process. The study shows that for vehicles with older (open-loop) fuel systems, there is enleanment of the combusted mixture. The net effect on legislated emissions would be a reduction in carbon-monoxide (CO) emissions. The effect on unburnt hydrocarbon (HC) and oxides of nitrogen (NOx) emissions is more complex, and both can either be increased or decreased depending on the base engine calibration.

Studies on vehicles fitted with closed loop fuel systems and three-way catalyst (TWC) systems show reduced CO emissions, and generally reduced total HC emissions as the ethanol content in fuel is increased up to 40%. From the data available, tailpipe NOx emissions on average increased by approximately 30% with a 20% by volume ethanol blend, compared with no increase for a 10% ethanol blend. In absolute terms, this 30% increase in NOx corresponds to approximately 10 to 15% of the current Australian emissions regulation for passenger vehicles, but could be as much as 50% of the new proposed emissions regulation (ADR 79/00). All studies show a much larger increase in NOx emissions when the ethanol blend content exceeds 30% by volume. This is almost certainly due to the closed loop controller reaching the limit of authority to increase the fuelling level delivered to maintain the desired air and fuel mixture ratio.

The available data on many unregulated emissions for ethanol blends greater than 10% is small. The data that is available indicates that aldehyde emissions will increase as the percentage of ethanol increases. Predominantly, this is due to the effect on acetaldehyde, with increases of more than 100% likely with ethanol blends of 10% or more by volume. Formaldehyde emissions are shown to remain relatively constant up to an ethanol blend of 30%. Other unregulated emissions of toxic and greenhouse gases are likely to remain similar to, or less than, the levels from gasoline only fuels.

Carbon dioxide (CO_2) emissions, a major greenhouse gas contributor, may be reduced as the ethanol content is increased. The reductions reported for ethanol blends up to 20%, however, are small and may not be significant, especially when considering the total fuel cycle. The total fuel cycle includes the CO_2 emissions produced during the manufacture of the fuel, which can vary substantially for ethanol depending on the production process, and hence dominate any small reductions in vehicle tailpipe levels. The fuel economy is expected to be reduced by approximately 7% for an ethanol content of 20% by volume in gasoline. This loss of fuel economy is virtually all due to the reduction in energy content (on a volume basis) of the fuel.

Evaporative emissions are likely to increase with higher blends of ethanol. The data shows a consistent increase in evaporative emissions measured during vehicle “hot soak” testing for fuels that contain ethanol. Future Australian emissions legislation will include a further “real time diurnal test” which is highly likely to exacerbate the problem. There is also a risk, with the use of high ethanol concentrations, of increased evaporative emissions from vapour permeating through some fuel system plastics.

Vehicle operability in terms of driveability and Wide Open Throttle (WOT) performance may deteriorate as the ethanol content of the fuel is increased up to 20% by volume. The extent of deterioration will be dependent on the age of the vehicle. The literature reviewed indicates conflicting views related to operability though there is a general view that those vehicles fitted with lean calibrated carburettors are likely to display the most significant deterioration across the driveability spectrum due to the enleanment caused by the addition of 20% by volume of ethanol. In terms of the newer vehicle fleet, those fitted with closed loop fuel injection systems, enleanment is likely deteriorate the cold starting performance. However this is likely to be dependent on the ability of the engines control system to maintain stoichiometry within the cylinder of the engine, a function related to the manufacturers control strategy. In respect to hot weather driveability, the newer vehicle fleet should be more robust and this is most dependent on the design of the fuel system within the vehicle in terms of the temperature it is subject to under hot soak conditions.

The anti-knock capability of high ethanol blends is not as simple as defined by the standard measurements of Research and Motor Octane Numbers, (RON & MON). While many authors present the octane advantages in terms of the increased RON and MON, those who have undertaken testing suggest that there is either a negative or at best a marginal benefit with ethanol blends beyond 5% by volume. It is likely that high engine speed knock will occur due to the increase in octane sensitivity the addition of 20% ethanol brings when added to the base gasoline. This is however dependent on the compounds used to make up the gasoline in Australia. Vehicles fitted with knock sensors will not exhibit the associated “pinging” sound, though depending on the reduction in spark advance may suffer reduced acceleration performance.

The impact of a 20% ethanol blend on engine durability of the Australian vehicle fleet is unclear. In terms of engine wear the literature reviewed is unclear leaving the only valid conclusion that further testing is required to obtain sufficient data to form a view. The issue of deposits is equally unclear. There is conflicting data with one very significant experiment in terms of size concluding there was no impact with up to 20% ethanol, while a detailed scientific experiment showed a definite deposit problem.

The literature studied indicates that there is a significant potential problem for those vehicles with fuel systems that have reached the ‘normal’ stabilised level of internal deposits which are passive to gasoline. Upon introducing these vehicles to a 20% ethanol blend, these deposits are likely be stripped away causing fuel filter blockages and plugging of fuel metering components.

Perishing and swelling of elastomeric and plastic materials making up the fuel system is highly likely on the older vehicle fleet when exposed to E20. The newer fleet may be less likely to show these problems as many of the components are globally sourced and therefore may be compatible with up to 10% ethanol blends giving some element of protection for an E20 blend. In any circumstance where the potential for a fuel leak arises, a potentially hazardous situation is created.

The potential for corrosion of the metal components of the fuel system has been identified by this study. Corrosion is likely to be a longer term issue as the corrosion process is relatively slow. However, the potential for a fuel leak is clear along with the potential hazardous situation. Within Brazil for example where 24% ethanol blends are common, metal surfaces within the fuel system have specific surface treatments to guard against corrosion.

When considering fuels of up to 20% by volume ethanol content for the Australian automotive market, many issues and uncertainties are raised. Some of the effects which may occur are difficult to judge with the current information available through literature searches. The major areas identified that require more investigation are as follows:

- Establishment of typical limits for closed-loop controllers operating with electronic fuel injection systems and TWC aftertreatment systems. The range of authority identified will provide a look-ahead for the capability of the system to cope with long term fuel system drift as well as ethanol content in the fuel.
- Measurements of evaporative emissions for ethanol blends higher than 10% by volume. Current data only covers up to an addition of 10% ethanol. This includes permeation effects with higher ethanol blends.
- Measurements of unregulated emissions for ethanol blends higher than 10% by volume. Current data only covers up to 10% by volume ethanol content. The measurements should include both tailpipe (for open-loop and closed-loop control fuel system technologies) and evaporative emissions of unregulated emissions.
- Detailed, well defined vehicle operability assessments with 20% by volume ethanol blended fuel. The impact on the operability of both open loop and closed loop fuel systems vehicles is unclear. The assessment should include both vehicle driveability and anti-knock impacts.

It is believed that the majority of the shortcomings of the currently available data will be effectively overcome by the current contracted scope of work included in the Environment Australia Project: 'Market Barriers to the Uptake of Biofuels – Testing Petrol Containing 20% Ethanol (E20) '.

Though the current program does include testing to determine the impact of the 20% ethanol blend in terms of the reported anti-knock property, it does not allow a detailed or quantitative analysis to be undertaken. It is therefore recommended that additional testing of engines be performed. This would typically involve operating engines in fully instrumented engine dynamometer test cells to gather data targeted to understand this impact.

The other major area identified is the lack of data on the long-term emissions and fuel system durability impact of a 20% ethanol blend fuel. Specifically, data is required to understand the following effects;

- catalyst durability impact,
- the impact on the long term adaptation limits of the closed loop controller taking into account the effects of vehicle, and
- the impact on the metal, elastomeric and plastic fuel system on new vehicles.

These effects can be established via completion of the 80,000 km durability testing on the mileage accumulation chassis dynamometers. It is recommended that this testing be adopted to provide a suitable analysis of the effects of a 20% by volume ethanol blend fuel.

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9 ACRONYMS AND TERMINOLOGY

ADR	Australian Design Rules
AFR	Air Fuel Ratio
AGO	Australian Greenhouse Office
CO	Carbon Monoxide
CSIRO	Commonwealth Scientific and Industrial Research Organisation
ECU	Engine Control Unit
EFI	Electronic Fuel Injection
EPA	Environmental Pollution Agency
FTP	Federal Test Procedure
FVI	Fuel Volatility Index
GMR	General Motors Research
HC	HydroCarbon
ISD	Intake System Deposits
kPa	kiloPascals
MON	Motor Octane Number
NOX	Nitrogen Oxide
PI	Proportional Integral
psi	pounds per square inch
PULP	Premium Unleaded Petrol
RON	Research Octane Number
rpm	revolutions per minute (engine speed)
RVP	Reid Vapour Pressure
SAE	Society of Automotive Engineers
SHED	Sealed Housing for Evaporative Determination
T50	Temperature at which 50% evaporates
T90	Temperature at which 90% evaporates
THC	Total HydroCarbons
TWC	Three Way Catalyst
ULP	Unleaded Petrol
WOT	Wide Open Throttle

% used in reference to ethanol is % v/v
% used in reference to oxygen is % m/m