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Assessing compatibility of fuel systems with bio-ethanol and the risk of carburettor icing. Final Report.

Stephen Wall
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Executive Summary

This document represents the final report of work performed under the Department for Transport (DfT) project “Assessing compatibility of fuel systems with bio-ethanol and risk of carburettor icing”, tasked through AEA warrant number 14717211. This final report satisfies Deliverable 4 of the project, and updates and expand upon the interim summary provided by email on 26th March 2010, the first and second quarterly progress reports submitted on the 30th April 2010 and the 30th June 2010, the second milestone report issued on the 30th July 2010 and the draft final report issued on the 30th September 2010.

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1 Introduction

This document represents the final draft report of work performed under the Department for Transport (DfT) project "Assessing compatibility of fuel systems with bio-ethanol and risk of carburettor icing", tasked through AEA warrant number 14717211. This final draft report satisfies Deliverable 3 of the project, and updates and expand upon the interim summary provided by email on 26th March 2010 [1], the first and second quarterly progress reports submitted on the 30th April 2010 and the 30th June 2010, the second milestone report issued on the 30th July 2010 and the draft final report issued on the 30th September 2010.

1.1 Aims of the project

The aim of the project is to study the technical impact of the introduction of higher levels of bio-ethanol into petrol. This is in response to EU directive 2009/30/EC, which increases the maximum permissible content of ethanol in petrol from 5% to 10% [2].

The DfT has recognised that the design of fuel systems for older cars and motorcycles dates back to before ethanol was generally considered as a blend component for petrol. There is an evident concern that elevated levels of ethanol in petrol will therefore be incompatible with materials present in these older vehicles' fuel systems.

In addition, the higher heat of vaporisation of ethanol compared to petrol may cause fuel/air mixtures being introduced at temperatures below that for which the engine was designed. In the presence of significant quantities of water vapour, this could lead to the formation of ice particles that may block passages or otherwise affect engine components.

The project is therefore focussing upon the compatibility of fuel system materials with petrol-ethanol blends and their on the effect on carburettor icing.

1.2 Outline of approach

A broad outline of the planned approach for this project was provided within the proposal document submitted through AEA to the DfT. This approach was ratified by DfT at a kick-off meeting, at which further guidance on the scope of the project was provided. For example, it was agreed by DfT that socio-political issues, such as problems with supply, do not form part of the scope of the project and that the project should concentrate on road transport, drawing only on marine, and possibly aviation, in the event of overlap.

Underpinning the project has been a thorough search and evaluation of sources of information directly related to the properties of ethanol and the effect of its presence as a blend component in petrol. These include industry contacts, technical documents in the public domain, as well as conventional academic papers.

2 Penetration of ethanol into the UK petrol market

The British Standard for unleaded petrol BS EN 228 [3] allows up to 5 % ethanol as a blend component. However this does not mean all UK petroleum companies are retailing petrol containing ethanol. In order to determine how extensive ethanol use is and therefore how widespread potential problems could be, petroleum companies were contacted and their use of ethanol discussed. A brief summary of the information gathered during these discussions is reported here.

Due to its strong affinity for water, transportation of petrol/ethanol blends through multi product pipelines is not possible as the pipelines tend to contain some moisture which would be absorbed by the ethanol and cause phase separation. Instead the ethanol is blended into the petrol basestock at road tanker loading terminals just before delivery to retail sites. Construction of these blending facilities requires considerable investment and delay, hence the UK petroleum companies have led with biodiesel, which can be blended at the refinery, to meet their Renewable Transport Fuel Obligations. The change in the British Standard for road diesel, BS EN 590, allowing up to 7 % biodiesel in road diesel may further delay ethanol’s universal use [4, 5, 6].

Government figures indicate that the current usage of ethanol in petrol in the UK is equivalent to 2.8 % of total unleaded petrol sales [7]. However discussions with the petroleum industry and user groups indicate that although the coverage is widespread it is not uniform [8, 9, 10]. Typically petrol contains either no ethanol or 4 to 5 % depending on the geographical area. At this level (≤ 5 %) the retail pumps are not required to be marked as dispensing fuel containing ethanol.

A new version of BS EN 228 has recently been proposed that would allow two grades of petrol, one with a low oxygenate content (up to 5 % ethanol) the other grade could contain up to 10 % ethanol [11]. There is an unofficial agreement to maintain the low ethanol grade until at least 2013 [5, 6].

E85 (petrol containing approximately 85 % ethanol) blends are marketed for specially designed vehicles (flexible fuel vehicles).

3 Fuel system compatibility

Compatibility of the fuel system with E10 (petrol blends containing 10 % ethanol) is a concern as it can affect vehicle durability, vehicle drivability, fuel economy, emissions and safety.

The approach to this part of the project has been:

1. Summarise why fuel system compatibility may be an issue with E10 blends;
2. Conduct a literature review to determine what material compatibility testing has been reported;
3. Contact the OEMs and relevant industry organisations to identify the nature of materials used in vehicle fuel systems over the last 20 years;
4. Discuss past, current and potential compatibility issues with the OEMs and industry organisations;
5. Investigate the situation in other markets that have introduced E10 or plan to do so.

3.1 Vehicle fuel system compatibility with E10 blends

This section briefly summaries why E10 may give rise to fuel system compatibility issues that might lead to the complete failure of a component. This is expanded in subsequent sections.

3.1.1 Fuel filter blockage

Ethanol enhances the solvent properties of petrol in petrol/ethanol blends. Fuel system deposits that were previously stable may loosen, causing fuel filter blockage and by their scouring action increase wear of fuel system components.

3.1.2 Galvanic corrosion

Ethanol has a high conductivity compared to hydrocarbons and if electrically dissimilar metals are present galvanic corrosion may occur.

3.1.3 Enleanment

Ethanol contains about 35 % oxygen. If the air/fuel mixture is not adjusted to allow for this, the vehicle will run on a lean mixture which can cause problems with both drivability and overheating in the exhaust tract.

3.1.4 Drivability

Due to the potential for E10 blends to have a higher volatility than purely hydrocarbon fuels, hot fuel handling (poor hot starting, hesitation etc) may be an issue. Additionally ethanol has a high latent heat of vaporisation and this may affect cold weather drivability.

The potential impact of ethanol blends on carburettor icing is dealt with in a separate section.

3.1.5 Deposit formation

Increased levels of inlet system and combustion chamber deposits have been reported with the use of E5 and E10 blends compared to E0.

3.1.6 Material compatibility

With regard to material compatibility, ethanol differs from purely hydrocarbon fuels in three important ways:

- The relative size of the ethanol molecule.
- The presence of the polar hydroxyl group.
- The higher conductivity of ethanol and resulting petrol/ethanol blends.

These different properties can result in some fuel system elastomeric/plastic components being less compatible with petrol/ethanol blends than with hydrocarbon only petrol.

Some fuel system elastomers contain polar components and are partially stabilised by hydrogen bonding and other interactions These interactions may be vulnerable to substitution by the hydroxyl group resulting in the loss of structural integrity when exposed to petrol/ethanol fuels.

As ethanol is smaller and more polar than methyl tertiary butyl ether (MTBE) and other larger fuel oxygenates, there is a lower energy barrier for ethanol to diffuse into elastomer materials. When exposed to petrol/ethanol blends these materials will swell and soften, resulting in a weakening of the elastomer structure.

Petrol and ethanol blends can hold more dissolved water and associated impurities than neat petrol. This may result in enhanced corrosion of metallic components.

3.2 Fuel filter blockage

During the life of a vehicle deposits such as gums (fuel degradation products), rust and scale will tend to build up in the fuel system. Often the gums act as binders for the inorganic deposits. If the vehicle is switched from E0 to E5 or E10 the increased solvent properties of the ethanol blend will loosen the binding gums and destabilise the fuel system deposits which will be transported to the fuel filter causing accelerated blockage. Sometimes this can result in loss of power and eventually complete vehicle failure [12, 13, 14, 15, 16].

In some cases where the E10 fuel is not compatible with material present in the fuel system, the material can be attacked and the resulting debris can result in filter blockage or worse. For example:

- Stripping of fuel tank sealant leading to fuel filter blockage and eventual complete fuel system fouling [17]
- Extraction of binding agent from glass fibre reinforced fuel tanks [14] (glass fibre reinforced polyester and epoxy resins being particularly affected [18])
- Stripping of protective plating from the interior of a vehicle fuel tank, for example terne plate, leading to filter blockage [19].

It has been suggested that this filter blockage can be simply dealt with by changing the blocked filter [19]. The possible scenario is very much more serious than that. For instance, a sudden loss of power on a motorway is possible (as opposed to gradual loss), followed by an unpowered cruise across three lanes of traffic and a fuel filter change on the hard shoulder represents a very serious risk to the safety of the vehicle occupants and other road users in the immediate vicinity.

A study conducted by Orbital evaluated the effects of E5 followed by E10 blends on a selection of vehicles, some of which are common to the UK market [12]. Both the blends tended to increase deposit on fuel filters. One vehicle, out of fifteen, failed to start due to a blocked filter.

The majority of petrol in the UK has been treated with detergency additives for years, so this may already have removed deposits from vehicle fuel systems. E5 has already been introduced into some areas of the country. If filter blockage is going to be a significant issue it would be expected that some reports would have already been noted. A major UK motoring association has been requested to report any such problems noted by its repair and recovery section. No such reports have been received.

3.3 Galvanic corrosion

Galvanic corrosion is an electrochemical process in which one metal corrodes preferentially when in electrical contact with a different type of metal and both metals are immersed in an electrically conductive liquid.

Table 1 shows the electrical conductivity of ethanol, water and selected hydrocarbons typically contained within petrol.

Liquid	Conductivity (mhos/cm)
Ethanol	1.35×10^{-9}
Deionised water	5×10^{-8}
Hexane	1×10^{-18}
Heptane	1×10^{-15}
Toluene	1×10^{-14}
Xylene	1×10^{-15}

Table 1 Indicative conductivity of various liquids

Ethanol has similar conductivity to water and is a significantly better conductor than hydrocarbons. Thus generation of electrode potentials between metals can set off the corrosion process. Metals that show good resistance to alcohol blends when exposed individually may be rendered susceptible to attack when coupled electrically to another electrically dissimilar metal. An example being the corrosion of steel and aluminium exposed to ethanol in a bulk storage facility. The aluminium was subsequently anodised which solved the problem [20]. Pairs of electrically dissimilar metals are aluminium - steel, aluminium – brass and zinc - brass.

In South Africa, vehicles fuelled on Sasol petrol seem to have suffered significant carburettor corrosion. Sasol petrol contains 12% of mixed alcohols comprising ethanol (67 % w/w), propanol (18 % w/w) and higher alcohols (15 % w/w) [21]. It was suspected that one of the alcohols present was responsible for the corrosion problems. Letcher et al [21] demonstrated that the propanol present in the fuel allowed relatively high levels of water to be dissolved in the fuel while the fuel was stored in service station tanks. This wet fuel would not phase separate due to the presence of the propanol. It was postulated that the wet fuel would be transferred into the carburettor bowl. If left to hot soak the fuel would evaporate leaving the water which would cause the observed corrosion. The problem was resolved via a fuel additive route [22]. Ethanol was not implicated as causing the problem [21].

Discussions have been held with the sole manufacturer of SU carburettors and Amal carburettors, a UK based company [23]. They have received reports from the US and Australia of corrosion in Amal carburettors where bronze is in contact with zinc. The corrosion occurs when the vehicle is placed into storage with an undrained fuel system. After only a few weeks corrosion occurs producing a fine white powder that blocks the carburettor jets. The solution is to completely drain the fuel system prior to the vehicle being stored.

This company has also undertaken compatibility ‘soak’ testing of its products in petrol/ethanol blends (E10 and E85). They have observed degradation and corrosion of brass components. To prevent this degradation, it has been found necessary to modify the carburettors. Elastomeric components have to be made from Viton, carburettor needles have to manufactured from nickel silver alloy rather than brass and jets originally made from brass have to be manufactured from manganese bronze alloy.

Clearly even at the current level of ethanol in petrol there is still potential for galvanic corrosion in carburettors. Modification of the materials used in the construction of the carburettor seems the only solution if these components are exposed to petrol ethanol blends.

3.4 Enleanment

The vast majority of modern vehicles use electronic fuel injection with some form of compensating ‘closed loop’ or feedback control in some areas of the engine operation envelope. The feedback is via an oxygen sensor in the exhaust that directly measures oxygen content in the exhaust gases. The engine management system employs this signal to calculate the mean air/fuel ratio of the mixture entering the engine cylinders. If the actual air/fuel ratio differs from the desired air /fuel ratio held in the engine map then the fuel delivery is adjusted to bring it back to within the desired range. It should be emphasised this closed loop operation only operates within part of the engine operating envelope, usually within that part used for emissions testing. In other areas, for example when operating at wide open throttle (WOT), the system becomes open loop with no feedback.

Ethanol contains approximately 35 % oxygen by weight and so will lean off the air/fuel mixture. During operation in the closed loop zone, the engine management system compensates for this leaning effect by increasing the flow of the fuel. In the uncompensated open loop engine operation zones no compensation of the air/fuel ratio is possible and the engine mixture becomes lean. A lean mixture results in hotter combustion, a greater tendency to cause engine spark knock and hotter exhaust gas temperatures (higher combustion temperatures will also increase NOx formation). During vehicle trials, exhaust temperature increases of 50 °C have been observed but are generally below 30 °C [12].

It should be emphasised that the impact of enleanment depends on the relative richness of the base engine calibration. If this is inclined toward operating on the lean side the impact may be significant [24].

It is unlikely that carburettored vehicles and those fitted with mechanical or early electronic fuel injection will be able to make sufficient adjustment to the mixture strength while running on E10. The could result in drivability issues. The Federal Chamber of Automotive Industries in Australia states poor drivability is one reason why it does not recommend ethanol petrol as being suitable for use in vehicles manufactured before 1986 when mixture preparation via a carburettor was the predominant technology [32]. A similar approach may be appropriate for the UK market.

3.5 Drivability

The potential exists for E10 blends to exhibit a higher vapour pressure than conventional blends (E0). This could result in the E10 blend vaporising prematurely in the fuel system prior to the carburettor or fuel injector. This can happen when the vehicle is left to 'hot soak' i.e. the engine and associated cooling devices have been switched off while the engine is still hot. The likelihood of the petrol vaporising will depend on the vehicle's fuel system design, ambient temperature and pressure.

Premature vaporisation of the fuel can result in vapour lock and fuel starvation leading to hot start problems, hesitation and even stalling when the operator attempts to restart and drive the hot vehicle away. Some older vehicles may experience 'running vapour lock' when operating under high speed and high load conditions.

There has been a considerable number of multi-vehicle road trials reporting the drivability of vehicles fuelled on E10 compared to E0 [12, 19, 26, 27, 28, 35]. At least one other road trial has been conducted on E10 [29] but that was in the USA and the vehicles were known to be compatible with E10 [30, 31].

Of the trials identified in the current review the only trial to report drivability problems was conducted by Orbital in Australia and employed a range of passenger cars, with manufacturing dates ranging from 1982 to 2000 [12]. Some of these vehicles are similar to models being used in UK. Carburettored vehicles manufactured between 1982 and 1997 were evaluated on E5 and all were found to have drivability issues. Table 2 summarises the Orbital studies findings for drivability and material compatibility. These hot start and drivability issues, although unsatisfactory for the user were not considered safety issues.

In addition to drivability the Orbital study investigated vehicle performance, including acceleration times and distance covered from a standing start. Generally there were improvements in acceleration when operating on ethanol blends although some vehicles showed degradation in certain areas.

As already mentioned degradation of drivability is one of the stated reasons why the Federal Chamber of Automotive Industries in Australia does not recommend ethanol petrol as being suitable for use in vehicles manufactured pre 1986 [32]. A similar approach may be appropriate for the UK market.

Work by CONCAWE indicates that modern multi point fuel injection (MPI) vehicles are much less susceptible to hot weather drivability problems than older vehicles [33] Modern fuel injection systems can adjust the fuel pressure in the system to prevent vapour lock [34]. A test programme evaluating the drivability of eight modern vehicles (direct injection spark ignition (DISI) or MPI fuel systems) fuelled on ethanol blends demonstrated that [35]:

- Hot weather drivability degradation only occurred at high temperatures on fuels with volatility beyond the summer limits of BS EN 228, the European standard for unleaded petrol.
- The effects of ethanol on cold weather drivability were varied, some vehicles demonstrating no sensitivity to ethanol, while splash blending of ethanol in some fuels improved drivability. It was thought that the improved drivability was due to increased volatility of the fuel rather than the presence of the ethanol per se.

Technology				**E5 Result**		**E10 Result**	
	Make	Model	Model Year	Performance /drivability	Material Compatibility	Performance/ drivability	Material Compatibility
Fuel injected	Hyundai	Excel	1999	OK	OK	OK	?
	Nissan	Pulsar	2000	OK	OK	OK	?
	Ford	Festiva	1996	OK	OK	OK	X
	Honda	Civic	1997	OK	OK	OK	?
	Nissan	Patrol	1999	OK	OK	OK	?
Carburettor	Toyota	Hilux	1997	X	X	X	X
	Mazda/Ford	323/Laser	1986	?	X	?	X
	Toyota	Corolla	1991	?	?	?	X
	Holden	Commodore	1985	X	?	Not Assessed	
	Ford	Falcon	1982	?	?		
	Ford/Mazda	Laser/323	1984	?	?		
	Toyota	Corolla	1984	?	?		
	Mitsubishi	Magna/Sigma	1986	?	?		
	Toyota	Land Cruiser	1985	?	?		
	Nisan	Bluebird	1985	?	?		
	Holden/Nissan	Camira/Astra/ Pulsar	1984	X	?		

Table 2 Summary of Orbital's trial driveability and material compatibility results

3.6 Deposit formation

The Orbital study identified formation of heavy deposits on the stems and tulips of inlet valves in some vehicles. The extent of the deposits was such that the valves had ceased to rotate. It was believed that there was potential for the deposits to fall off and become trapped between the inlet valve and its seat causing loss of compression pressure. It is unknown if this would be an issue in the UK as inlet system detergency fuel additives have been in use for many years.

Orbital also reported increased deposit formation on piston crowns and piston ring grooves in some vehicles. This could increase the risk of spark knock and more seriously could lead to the risk of engine failure due to piston seizure.

3.7 Material compatibility

It was agreed at the start of this project that an appropriate approach for this assessment would be to consider the material compatibility of ethanol petrol blends with all potential vehicle fuel system materials while simultaneously attempting to determine what material types are actually found in fuel systems.

Material compatibility can be divided between compatibility with metals and non-metals.

3.7.1 Material compatibility with metals

Two issues have to be considered here:

- corrosion due to incompatibility with petrol/ethanol blends and
- corrosion due to contact with phase separated ethanol and water

Considerable information has been gathered from reviews, reports and summaries of studies investigating the compatibility of petrol and ethanol blends with metallic materials [12, 18, 19, 24, 26, 27, 29, 31, 37, 38, 39, 20, 41, 42, 43, 44, 45, 167].

Care has to be taken in interpretation of the information. To give two examples that could be misleading:

- A CONCAWE report [18] recommends carbon steel and aluminium for ethanol/petrol handing situations.
- A laboratory study [44, 167] evaluated 19 metallic species, including four types of aluminium alloy and brass, in E10 and E20 blends, three aluminium alloys were judged as satisfactory as was brass.

Unfortunately it is known from field experience that E10 blends can severely corrode aluminium components, leading to catastrophic failure [46]. Also carbon steel can suffer severe corrosive attack if the fuel contains water [37]. Brass components in carburettors are known to corrode when exposed to E10 [23].

A fundamental problem interpreting the results is that the exact type of alloy is often not reported.

Another issue is the judgement of the workers evaluating the test results as to whether the extent of corrosion is significant or not. For example a US Agency and University conducted a series of studies to evaluate the effect of E20 on materials. In these studies tarnishing of metallic species was not judged significant [44, 167]. In another study, by the same workers, material compatibility in a vehicle trial was judged to be satisfactory if there were no drivability issues, rather than by stripping and inspecting fuel system components [29]. This work was later criticised for its lack of rigour [47].

A key study was conducted by Orbital Australia PTY LTD using a fleet of vehicles some of which are common to the UK market [12] see Table 2. They reported a very detailed study of the compatibility of E5 and E10 with vehicle operation and material compatibility. Instead of identifying the materials used to construct various fuel system components the whole component was soak tested. All the carburettored cars in the study were judged to contain materials that had doubtful material compatibility with E5. Of particular concern was tarnishing and corrosion of carburettor components manufactured from brass and used to meter fuel.

As was mentioned earlier a carburettor manufacturer has conducted compatibility testing of its products with petrol/ethanol blends and has identified corrosion of metallic components as an issue, requiring replacement of brass components with more resistant, but more expensive, alloys [23].

Considering phase separation due to contamination by water, this is potentially a serious problem because only 0.5 % water is required in an E10 blend to cause phase separation [38, 48]. The result is that two distinct liquid layers will form, the lower layer is an ethanol rich aqueous layer.

Monteiro *et al* investigated the effect of anhydrous and wet ethanol on materials commonly found in automotive fuel systems [37]. It was determined that wet ethanol was very much more aggressive than dry, with corrosion rates produced by wet ethanol being up to four hundred times faster than those caused by dry ethanol blends. This increase in rate of corrosion was attributed to the presence of ionic species, from the impurities in water promoting electrochemical reactions.

Hodam [43] has also provided an example of extreme corrosion in a steel underground storage tank caused by E10 phase separation.

Effect of phase separation on engine operability

The aqueous ethanol phase can only enter a vehicle fuel system if:

- The fuel at the service station has phase separated or,
- Water is added directly to the tank or,
- The fuel becomes saturated by water vapour from the air.

If phase separation did occur it is conceivable that the ethanol rich aqueous layer could enter a vehicle's fuel system and actually be combusted in the vehicle's engine. In a two stroke engine the aqueous ethanol could compete with the blended oil for bonding to the metal engine parts, reducing lubrication and possibly resulting in engine damage. In a four stroke engine, the aqueous ethanol phase would combust potentially resulting in serious or catastrophic damage [49].

Fortunately discussions with the petroleum industry indicate phase separation at service stations is unusual. One company reported that there have only been two instances in approximately three years, caused by addition of petrol/ethanol blends to very wet service station tanks [50]. Another petroleum company report fewer problems than anticipated with E5 blends [51]. The E5 blends act as powerful desiccant, drying out the fuel storage system. Phase separation will only occur when there is a major ingress of water - possibly through faulty inspection covers - during heavy rainstorms.

The addition of water to a vehicle fuel tank could occur through accidental addition (i.e. rain) or deliberately (i.e. a criminal act). The owner should take precautions when filling the tank with fuel and at other times ensure the fuel filler cap is locked.

It has been calculated that it would take some years for a one gallon volume of petrol and ethanol to become saturated due to water vapour in the air [49], hence it is highly unlikely to occur.

It can be concluded that phase separation of E10 fuel followed by the ethanol rich aqueous phase entering a vehicles fuel system and causing significant corrosion or engine damage will be possible but rare.

3.7.2 Material compatibility with non metals

Black reviewed the available technical data for the effect of methanol and ethanol fuel blends on materials compatibility with non metals [38]. He reported findings by Abu-Isa [52] that demonstrated the effect of various oxygenated blends on elastomers. This work clearly demonstrates that petrol / ethanol 10 % blends are more aggressive to elastomer attack than either petrol or ethanol and has been confirmed by other workers [53, 54].

It has been shown that fluorinated elastomers are more resistant to attack than non-fluorinated elastomers [38]. Further it has been demonstrated that increasing the fluorine content of elastomers correlates with their degree of resistance [53, 54]. Viton A , the least fluorinated grade being reported as unsuitable for storing ethanol blends [43].

A more recent US study, by Jones et al [44, 55], attempted to identify the range of elastomers and plastics employed in vehicle fuel systems and examine the effect of E10 and E20 blends. Eight materials included in the study were:

- Acrylonitrile butadiene styrene (ABS)
- Nylon 6
- Nylon 66
- Polybutylene terephthalate (PBT)
- Polyethylene terephthalate (PET)
- Polyetherimide 1010 moldable (PEI)
- Polyurethane 55D-90Adurameter hardness (PUR)
- Polyvinyl chloride flexible version (PVC)

Four materials ABS, PUR, PVC and PBT were all affected by all three fuels to some degree. ABS failed after one week. PUR, PVC and PBT showed changes that caused concern.

The workers experienced some difficulty in correctly identifying the types of elastomers and plastics as demonstrated at the end of the study when it became apparent that some materials (PUR and PVC) not used in vehicle fuel systems had been evaluated. The lack of severity in the rating method employed in this study may also be open to question. Discolouration of elastomers was not considered significant by Jones et al, whereas other studies classed discolouration as attack and signs of incompatibility [12].

Although some of the results of Jones et al work is in part confirmed by other studies including Leng and Nihalani [20, 56], other workers report more aggressive attack by petrol/alcohol blends [18]. For example Jones et al concluded Nylon 66 was compatible whereas a report by CONCAWE states it is not.

The Orbital study employed an apparently very severe rating system for tested components [12]. All of the non-metallic components in the carburettored vehicles studied were judged as having doubtful or unsatisfactory material compatibility with E5. Similarly all of the fuel injection vehicles, studied contained fuel system components that were judged as having doubtful or unsatisfactory material compatibility with E10, see Table 2.

3.7.3 Material compatibility field experience of E5/E10 blends

This section summarises field experience of E5 and E10 blends material compatibility.

Nihalani et al observed increased failure of elastomeric components in the fuel systems of two wheeled vehicles as E5 blends were introduced into the Indian market [56]. Laboratory testing of elastomers showed that normal acrylonitrile butadiene rubber (NBR) was not resistant to attack from E5 blends and as the aromatic content of the fuel increased, the resistance of the NBR to attack decreased. NBR with a higher acrylonitrile content and a fluorinated polymer were resistant to attack.

Shanmugam et al reported that field experience in India had shown E5 blends could be used in current petrol engines without detrimental effects [24]. They evaluated the effect of E10 blends on the performance, durability and emissions of 1.2 litre and 1.4 litre multi point fuel injection (MPFI) engines. Components in the fuel system, primarily aluminium alloy metallic components and PVC and NBR fuel hoses, that were in contact with the E10 blend were identified and inspected before and after extended road trials. Durability of the components was found to be acceptable.

Jaroonjitsathian et al report the experience of the introduction of E10 into the Thai petrol market, specifically its effect on motorcycle performance. Signs of premature component wear were noted with the use of E10 [26, 57]

Agarwal reports the Brazilian experience with ethanol blends [58]. In order to make vehicles more durable when employing ethanol blends, various fuel system components required modification including:

- Zinc steel alloy fuel lines were changed to cadmium brass.
- The tin and lead coatings (terne plate) of fuel tanks were changed to pure tin.
- Cast iron valve housings were changed to iron cobalt alloy.

Within Europe the high pressure fuel pump of a first generation direct injection petrol vehicle (model year 2004 – 2006) was found to be incompatible with E10. This was attributed by the OEM to the pumps high aluminium content [46].

It has been reported that in France E10 is damaging cars registered pre 2000 [59, 60]. It is claimed that material compatibility problems with metallic fuel tanks and elastomeric fuel hoses are causing widespread breakdowns. It is also reported that in 2009 the French Government advised owners of vehicles aged nine years and older not to use E10 [59]. The French Government is maintaining grades of petrol with lower ethanol content for vehicles not compatible with E10.

In the UK:

- cases of fuel hose failure after approximately six months running on E5 have been reported, the nature of the fuel hose is unknown but the replacement hoses are also failing after six months suggesting the OEM is still supplying parts not compatible with E5 [61].
- Increased reports of fuel pump failure due to fouling of pumps by debris from failed in-tank fuel hose, attributed to the fuel hose being incompatible with ethanol in petrol [62].

- vintage vehicles are reportedly suffering hot fuel handling problems which have been attributed to the use of E5. Corrosion of vehicle components and the stripping of sealants has also been reported [63].

A major UK motoring association has been informally requested by QinetiQ to report any increase in fuel related breakdowns. Figure 1 shows fuel related breakdowns from September 2009. There does not appear any clear trends and it is recommended that the situation is monitored as the use of ethanol containing petrol increases.

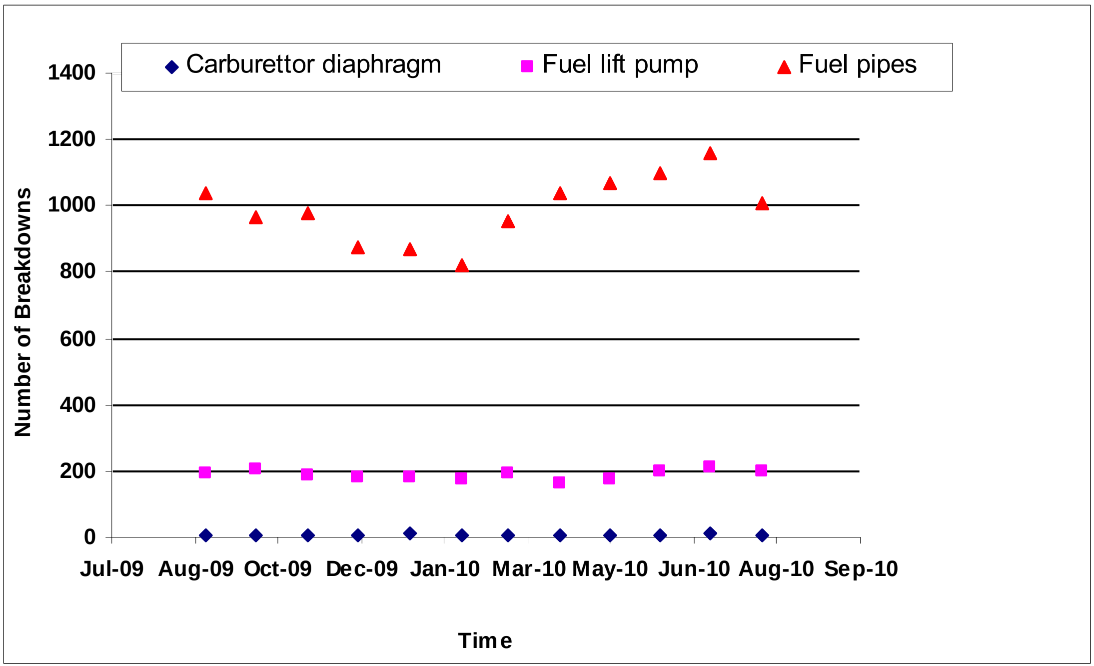

Figure 1 Fuel related breakdowns as identified by a UK motoring association

In the USA, Downstream Alternatives Inc reviewed, in 1997, the compatibility of oxygenated (ester and alcohol blends) petrol with US vehicle fuel system materials [31, 41]. It reports that there appear to be very few material compatibility issues with E10 blends. In addition they note that Chrysler, Ford, General Motors, Nissan and Suzuki recommend the use of reformulated (i.e. oxygenated) petrol. It also reports that motor cycle manufacturers including Harley Davidson, Honda and Kawasaki allow the use of E10 blends in their vehicles. It is generally reported in the literature that US ground vehicles have been compatible with E10 since the late 1980s. However investigation of internet automotive discussion forums indicates there are still significant compatibility problems with E10 in the US [64, 65, 66, 67, 68], not only with ground vehicles. Some motor boat fuel tanks manufactured from glass fibre [14] (glass fibre reinforced polyester and epoxy resins) are attacked by petrol ethanol blends.

3.8 Summary of material compatibility with E10

This is a very ambiguous area. What defines a compatible material varies from study to study, for example;

- The acceptable swell of elastomers has been reported as [42]:

- Dynamic applications – up to a 10 – 15 % swell can usually be tolerated.
- Static applications – up to 30 % swell in an O ring volume can be tolerated.

- Another stated view is that if the E10 has no worse effect than a previous fuel that demonstrated no field problems then the E10 has acceptable material compatibility [55], with the proviso that severe attack of the elastomer by a fuel is not acceptable.
- Other workers view tarnish or discolouration as enough to rate material compatibility as 'doubtful' [12].

The following Table 3 has been compiled from the results of studies identified during work on this project. Unfortunately many studies do not specify the exact type of alloy or grade of elastomer. Hence the table is for guidance only and is not a definitive summary. Where contradictions occur between studies the worst case has been tabulated.

Material	Suitable	Not suitable
Metals	Carbon steel (dry fuel only) Stainless steel Bronze 1018 Steel Nickel Plated 1018 Steel Zinc Tri-chromate plated (Hexavalent) 1018 Steel Zinc Di-Chromate Plated (Hexavalent Free) 1018 Steel Zinc-Nickel Plated	Zinc and galvanised materials Brass Copper Terne plate (lead/tin coated steel) Aluminium Magnesium alloys Zamak 5
Non metals	Acetal Acetal Copolymerised Polyoxymethene [69] Polyethylene Teflon Fibreglass-reinforce plastic Buna-N (hoses and gaskets) Fluorel Fluorosilicomne Polysulphide rubber Viton (not A grade) Acrylic Rubber (ACM) Epichlorohydrin Homopolymer (CO) Epichlorohydrin Ethylene Oxide Copolymer (ECO) Polychloroprene (CR) [Neoprene]	Polyurethane Polymers containing alcohol groups Fibreglass-reinforced polyester and epoxy resins Shellac Acrylonitrile butadiene styrene (ABS), Polyvinyl Chloride flexible version (PVC) Natural rubber Polyethylene Terephthalate (PET) Cork Petseal (trade name) Nitrile Rubber (NBR) [Buna N] with low acrylonitrile (CAN) content Viton A

Material	Suitable	Not suitable
	Nitrile Rubber (NBR) [Buna N] with medium acrylonitrile (CAN) content Nitrile Rubber (NBR) [Buna N] with high ACN content Nitrile/PVC blend (OZO) [Paracril] Polybutylene Terephthalate (PBT) Polyetherimide 1010 moldable (PEI) Polyamide 12 conductive version (PA 12) [Nylon12]* Polyphtalamide (PPA)* Polypropylene (PP)* Polyoxymethylene (POM)* Zytel (HTN)* Polyphenylene sulphide (PPS)* [162] Paper Leather	Polyamide 6 (PA 6), [Nylon 6] Polyamide 66 (PA 66) [Nylon 66] PVC

*compatible with E85 workers assumed compatible with E10 [55]

Table 3 Compatibility of materials with E10

It is strongly recommended that any component is extensively evaluated in its application prior to commercial release, i.e. a vehicle fuel pump body constructed from an aluminium alloy is tested on laboratory rig and in vehicles, the alloy should not just be soak tested using accelerated laboratory testing methods.

3.9 Discussions with industry and motoring organisations

Although the literature does provide some information on materials used in vehicle fuel systems, very little guidance is provided on the chronological use of materials over the last two decades in the UK market. OEMs and others in the industry were therefore contacted in an attempt to obtain this information

Two electronic fuel injection (EFI) equipment manufacturers, the European Plastic Fuel Tanks and System Manufacturers Association and the European Association of Automotive Suppliers have been contacted requesting information on the materials used in vehicle fuel systems [70, 71, 72, 73] . The latter two organisations did not respond.

One EFI manufacturer has stated that the first generation of direct injection petrol fuel high pressure pumps from all manufacturers are affected by corrosion caused by alcohol if exposed to E10. No vehicle fitted with these types of pumps can operate on E10. Production of these pumps commenced in 1999/2000 and vehicles were sold with this pump type until 2007.

This EFI manufacturer also provided a list published by the German automobile club (Allgemeiner Deutscher Automobil Club) which lists vehicles that are compatible with EN 228 [168]. This EFI manufacturer was concerned about the vapour pressure waiver being introduced into EN 228 (the European Standard for unleaded petrol) which they fear could affect ‘engine function’ [11]. If so, the number of vehicles regarded as compatible with E10 would be reduced [74].

Unfortunately this EFI manufacturer reported they have no knowledge of vehicle fuel systems as a whole and have provided a contact at the VDA (German Car Manufacturers Association) who may be able to assist [74]. The VDA have agreed to provide an updated list of compatible vehicles when it is completed [75].

Another EFI manufacturer reported that the knowledge of petrol fuel systems is held outside the UK organisation. Despite requests they have been unable to trace an expert in their international organisation [76, 77].

Independent automotive engineering consultants have also been contacted requesting information regarding materials used in vehicle fuel systems over the last two decades [78, 79, 80] All state that they had no information. A fourth independent automotive engineering consultancy was also contacted but did not respond [81].

A global vehicle manufacturer was approached requesting information on the materials used in its vehicle fuel systems over the last twenty years [82]. We were informed that some information may exist, unfortunately they did not have the resources to identify and report it [83].

Contact has been made with other industry organisations i.e. a motoring associations [84], motoring clubs, a motoring foundation [85], the Society of Motor Manufacturers and Traders (SMMT) [86] and the Federation of British Historical Vehicle Clubs Ltd (FBHVC) [87]. The motoring foundation do not feel they can comment on this issue [88], but valuable information has been forthcoming from the other organisations.

A UK based motoring association is also attempting to gather information from the OEMs on the compatibility of E10 with their vehicles but have struggled to obtain data [89, 90, 91, 92, 93, 94]. The following is a brief summary of the information they have obtained.

- The elastomeric fuel tank filler hoses are failing on a particular model of camper van produced by a global vehicle manufacturer. As this has recently happened - since the introduction of E5 into the area where the vehicles have been affected - this problem has been attributed to the use of ethanol in petrol. The replacement hoses are also failing after six months, leading to the conclusion that the OEM is still supplying spare parts that are not E5 compatible.
- The UK representatives of the global vehicle manufacturer mentioned above were asked about their views on ethanol in petrol. The motoring association were told it ‘isn’t even on their radar’ and would be sorted out by the parent company.
- A smaller vehicle manufacturer informed the motoring association that they had not considered the effect of ethanol in ordinary petrol.
- Fuel pumps are being damaged by debris from incompatible ‘in the fuel tank’ hoses.

The FBHVC has also provided some useful information regarding the possible effect of E5 on older vehicles [63]. Its members are reporting material incompatibility with petrol which they have not seen before. These include corrosion of zinc components and removal of fuel tank sealant materials, (Petseal). These effects are attributed to ethanol in the fuel although no fuel analysis has been conducted. Hot start difficulties have also been reported and there is concern that the proposed waiver on vapour pressure for ethanol blends will make the situation worse [11].

The UK Motor Cycle Industry Association and manufacturers and importers of powered two wheelers into the UK have been contacted to elicit their views on ethanol in petrol, specifically regarding material compatibility and carburettor icing [95, 96, 97, 98, 99, 100, 101, 102, 103, 104, 105, 106]. The following is a summary of the information received:

- Triumph, all Triumph motorcycles have been compatible with E10 since at least 1994. From 1993 to 2008 nylon moulded fuel tanks were employed but due to vapour permeability concerns a switch back to steel tanks was made [96].
- BMW. BMW motorcycles have been E10 compatible for at least twenty years [107].
- Harley-Davidson. All motorcycles have been E10 compatible since the 90s [108].
- Kawasaki. Kawasaki Heavy Industries are still considering the effects of E10 and do not recommend its use [109].
- KTM. All models from 2000 are compatible with E10 [110].
- Yamaha. All models are compatible with E5 and some new models are compatible with E10 [111].
- Suzuki. All models have been compatible with E10 since 2005 [112].
- Honda. All models have been compatible with E10 since 1993 but carburettored vehicles could suffer poor drivability [164, 165].

One manufacturer has not responded.

An importer of powered two wheelers from China was also contacted. The manufacturer of these vehicles has informed the importer that no provision for the use of E10 in these vehicles has been made [113]. The importer expects material compatibility problems with these vehicles if they are fuelled on E10.

A UK based manufacturer of carburettors reports that they are unable to obtain reliable data from their suppliers regarding the compatibility of components with ethanol blends. They have therefore had to conduct their own compatibility testing [23].

Similarly a supplier of replacement parts to the historic motorcycle market is conducting its own field tests on replacement fuel tanks [114].

3.10 Fuel system compatibility summary

3.10.1 Fuel filter blockage

If fuel filter blockage was going to be an issue it would be expected that the introduction of E5 into the market place, be it a rather patchy introduction, would have seen a rise in the number of complaints regarding fuel quality and vehicle malfunction.

However fuel filter blockage represents a very significant safety hazard and information in the literature does not help predict the extent of the problem.

3.10.2 Galvanic corrosion

There is a potential for galvanic corrosion in fuel systems containing electronically dissimilar metals in the presence of petrol and alcohol fuels. This study has identified reports of corrosion in carburettors containing brass and zinc components. Corrosion inhibitors added to the fuel may reduce the problem but it is unknown if these additives are in universal use [115]. Modification of the carburettors using more corrosion resistant, but more expensive, materials will probably be necessary with the introduction of E10.

3.10.3 Enleanment

Enleanment will occur when the vehicle is operating in an open loop mode, i.e. at WOT for a modern fuel injection vehicle and all the time for an older carburetted vehicle.

Exhaust gas temperatures will increase slightly, usually to below 30 °C. Workers believe this order of temperature change is unlikely to affect component durability [12]. Greater increases in exhaust gas temperature could affect the long term durability of exhaust catalysts.

3.10.4 Drivability

A review of the literature has identified an Australian study evaluating the effects of E5 and E10 on a range of vehicles some of which were common to the UK market.

This study reported that a significant number of the carburettored vehicles tested had drivability issues. The Australian automobile industry do not recommend E5 or E10 as suitable for carburettored vehicles and a similar approach might be adopted for the UK market.

There appears to be hot weather drivability problems with older vehicles in the UK and if BS EN 228 is modified to allow a vapour pressure waiver for ethanol blends some in the industry believe many more vehicles will be incompatible with petrol ethanol blends.

Modern vehicles are much less susceptible to drivability problems and the use of E10 in these vehicles should not result in significant drivability problems.

3.10.5 Deposit formation

The majority of petrol supplied through retail sites in the UK has been treated with an inlet system detergency additive so it is unknown if the increased inlet valve deposits reported by Orbital will occur in the UK. It would appear that there is potential for increased combustion chamber and piston ring groove deposit resulting from the use of petrol ethanol blends. This could cause catastrophic engine failure due to piston seizure.

3.10.6 Material compatibility

Extensive data on the material compatibility of petrol-ethanol blends has been identified and summarised. Some of the information identified is contradictory and this is attributed to differences in test conditions and rating methods employed by different studies.

There appears to be extensive potential for material incompatibility problems, with both metallic and non metallic materials. Already reports are being received of material incompatibility with E5.

Carburettored vehicles are reported as being incompatible with E5 and above. However it is appreciated there will be exceptions, especially as the major manufacture of carburettors in the UK has modified the materials in its products to make them more compatible with ethanol blends. All first generation direct fuel injection petrol vehicles are incompatible with E10

3.11 The extent of the problem

Discussions with OEMs and other industry organisations and reviews of available literature have identified very little historical data regarding the materials used in vehicle fuel systems. Without this historical data, determining the detailed extent of the problem is not possible.

Reports from France following the introduction of E10 there indicate many vehicles ten years old and older are not compatible with E10.

In Germany 3.4 million vehicles are thought not to be compatible with E10 and the introduction of this fuel has been postponed.

Two documents identifying passenger cars and motorcycles that are compatible with E10 (one for the German market and one for the French market) have been identified [168, 169]. However some of the information contained in these lists is contradictory.

It is widely accepted that vehicles ten years old and older will not be compatible with E10 blends, though of course there will be exceptions to this. There are approximately nine million petrol passenger cars and light duty petrol vehicles in the UK that are ten years old or older, this equates to about 38% of the total petrol vehicle parc [116]. In addition to these vehicles there are thousands of relatively new first generation petrol direct injection vehicles in the UK, the last new vehicle probably being sold in 2007, that are not compatible with E10.

The average age for a petrol passenger car at the end of life is 13.13 years while that of a petrol light commercial vehicle is 15.09 years [117]. This essentially means that approximately half these vehicles will still be in use in 2013 when the proposed phase out of petrol blends containing 5 % of ethanol occurs.

It is reported that the majority of carburettored vehicles (passenger cars, light duty commercial vehicles and powered two wheelers) will not be compatible with E10. Again there will be exceptions to this. However at least 1500 new carburettored powered two wheelers are imported into the UK per annum. According to the manufacturer, these powered two wheelers are not compatible with E10. The average life of these vehicles is at least five years [118]. Again thousands of these vehicles will still be on the road in 2013 when the proposed phase out of E5 will occur.

The number of carburettored vehicles in the UK is unknown but 6000 new carburettors are manufactured in the UK each year. Approximately 75 % of the carburettors produced are for the UK market, fitted not only to historic and vintage vehicles' but also to relatively new vehicles, reportedly to enhance the latter vehicles performance. This business has grown by 10 % in the last 18 months [23]. Carburettored vehicles will continue to be present on the roads for the foreseeable future. These new carburettors are compatible with E10 as are the repair kits being supplied by the same manufacturer. However cheaper pattern parts are still being imported that are not compatible with petrol/ethanol blends.

If E5 is phased out by 2013 it is expected that the resulting problems will include:

- increased vehicle maintenance (replacing leaking hoses, cleaning of blocked filters),
- reduced vehicle life (for example fuel tank beyond economic repair) and
- possible catastrophic failure (fuel fires due to leaking hoses, piston seizure etc).

Table 4 summarises the potential vehicle problems, potential solutions and indicative costs. It should be noted the costs do not include labour, where an OEM or dealership have not supplied data the costs have been taken from an internet parts supplier. A systematic survey of costs has not been undertaken. The table is not exhaustive.

It should be emphasised that for some older vehicles, or small market value, the required modifications to make the vehicles compatible with E10 or repairs after damage by E10 will be such that the vehicle is beyond economic repair. Hence the effect of will fall disproportionately on the poorer members of society who run these older vehicles and cannot afford to purchase newer more expensive vehicles.

Potential problem*	Result	Cost of prevention / repair
Incompatible fuel hose	Fuel leak Fuel pump damaged by debris Blocked/reduced diameter hose/loss of power Blocked filter/ rapid loss of power Blocked injectors Fuel Fire	Replacement hose <£50 loss of vehicle/ risk to driver and passengers Replacement pump cost £200 -£300 Replacement of fuel filter <£50/ loss of vehicle/ risk to driver and passengers £100 per injector Loss of vehicle/ risk to driver and passengers
Incompatible in tank fuel hose	Blocked/reduced diameter hose/loss of power Blocked fuel filter/rapid loss of power Fuel pump damaged by debris Blocked injectors	Replacement hose <£50/ loss of vehicle/ risk to driver and passengers Replacement pump cost £200 -£300 Replacement of fuel filter <£50/ loss of vehicle/ risk to driver and passengers £100 per injector
Incompatible fuel tank	Blocked hose/ Blocked fuel filter/ rapid loss of power Fuel pump damaged by debris Blocked injectors Fuel fire	Replacement tank £100 £250-£300 [36] Loss of vehicle/risk to driver and passengers Replacement pump cost £300 [163] Replacement of fuel filter <£50/ loss of vehicle/ risk to driver and passengers £100 per injector
Incompatible carburettor	Degradation of drivability	Refurbished carburettor £85 [25]
Incompatible first generation direct injection fuel pump	Failure to start, run etc	Replacement pump £300 [163]
Increased deposit formation in piston ring grooves	Increased emissions Engine failure due to seizure	De-coke £? Replacement engine ~£2000

*not exhaustive

Table 4 Potential vehicle problems and costs of prevention/repair with the introduction of E10

The situation regarding historical and vintage vehicles (i.e. vehicles registered before 1973) should be mentioned. There are nearly half a million pre 1973 vehicles in the country. The related activity is worth over £3 billion to the UK annually with the export trade being worth over £300 million. Over 27000 people in the UK earn some or all of their living serving the historical vehicle movement [166]. Owners of these vehicles are reporting significant problems with E5 blends.

These include material compatibility and drivability issues. To maintain the originality of the vehicle it is not desirable to replace original incompatible parts with new compatible parts, nor is it always possible. Unfortunately the introduction of ethanol into petrol is more problematical for these vehicles than the phase out of leaded petrol. The lead could be replaced by a fuel additive. The ethanol is a component in the fuel and its effects can only be partially negated by the use of fuel additives, for example corrosion inhibitors.

To maintain this valuable business and asset consideration should be given to providing after market corrosion inhibiting fuel additives and preserving a specification for a zero ethanol grade petrol.

4 Carburettor icing

4.1 Outline of the problem

Carburettor system icing is a phenomenon experienced by vehicles operating under idle engine conditions when warming up or when cruising, typically under cool, humid ambient conditions. It occurs because of a reduction in temperature caused by vaporization of the fuel. This results in the air temperature falling below its dew point, so that the moisture condenses and then freezes onto carburettor components. The deposition of ice on components acts as a restriction to air flow, which can result in stalling or a loss of power, with clear implications for vehicle operation and safety.

The exact temperature and humidity range under which icing is manifested depends on vehicle design and the properties of the petrol, but as an approximate guide carburettor icing in ground vehicles is a potential problem when relative humidity is above 77 % and the ambient temperature is between -3 and 12 ºC.

4.2 Effect of carburettor icing

The purpose of this study is to understand the effect of bio-ethanol on carburettor icing. In order to achieve this, it is important to understand the mechanism that results in the problems observed.

It has been reported that adiabatic vaporisation of fuel in the carburettor typically reduces the intake air temperature by 15 to 20 ºC [119] and that in extreme instances this temperature drop can increase to 30 to 35 ºC [120]. The effect that such drops in temperature have will be dependent upon where the ice forms.

4.2.1 Idle Icing

When ice forms on the throttle plate, it will only have a significant effect on the air/flow stoichiometry when the throttle is nearly or completely closed, typically when the engine is idling. Under these conditions, the presence of ice impedes the flow so that the fuel air mixture entering the chamber is too rich for combustion. The mechanism is demonstrated in Figure 2.

This type of carburettor icing is commonly referred to as idle icing and occurs when the vehicle is warming up. The result is repeated stalling every time the vehicle comes to a halt, for example at traffic lights.

In addition, since the modification to air-fuel mixture represents a reduction in efficiency under idle operation, idle icing can also result in an increase in fuel consumption and in the emission of gases typical of inefficient combustion, carbon monoxide and hydrocarbons[121, 122].

For idle icing, the gradual increase in heat transferred from the engine as it warms up leads to an increase in the temperature within the carburettor and the problem melts away.

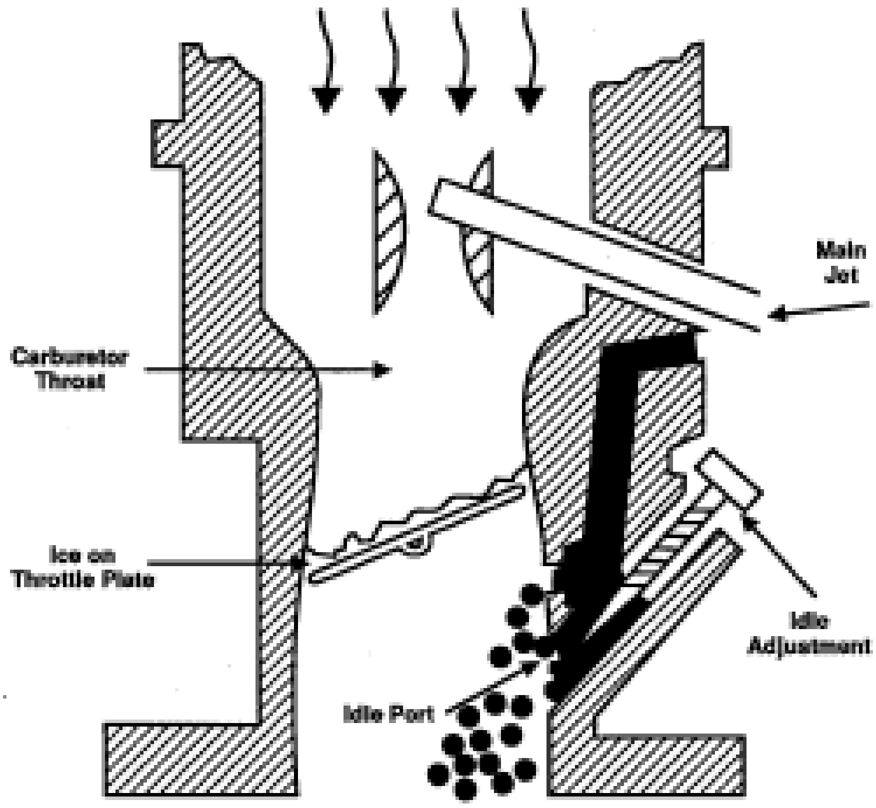

Figure 2 Throttle plate icing resulting in stalling at idle

4.2.2 Cruise Icing

Ice formation on the carburettor venturi occurs during high speed cruising, causing excessive air fuel mixture enrichment [123]. The impact is shown in Figure 3. The result is a loss in power and the possibility of stalling. Again, as this is a consequence of inefficient combustion, there will also be a reduction in fuel economy and increased emissions. This type of icing is generally known as cruise icing. Engine heat can resolve the problem by melting the ice so that the problem disappears.

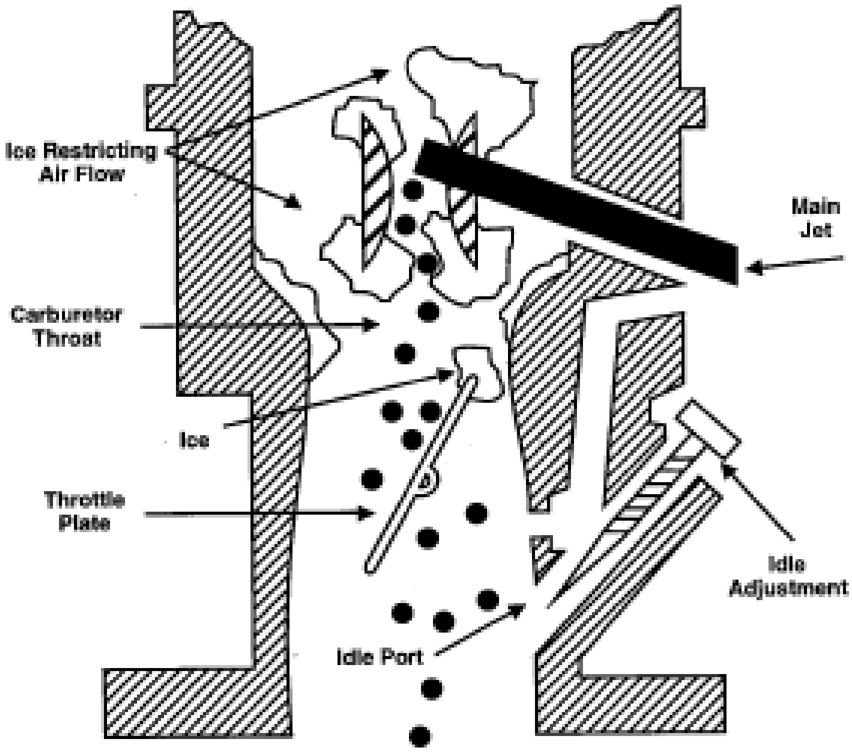

Figure 3 Ice formation in venturi area resulting in power loss

4.3 The importance of volatility

The extent to which carburettor icing affects a vehicle is dependent upon a number of factors, including the ambient conditions and vehicle design. For the current study, however, it is the physical properties of the fuel that are most likely to demonstrate the impact of bioethanol on carburettor icing. Of these, the volatility of the fuel has been identified as a critical factor in the process of carburettor icing. This has been the subject of a number of papers already obtained during the ongoing literature review [123, 124, 125, 126, 127]. As a fuel vaporises it absorbs heat from its surroundings, the faster the fuel evaporates (i.e. the more volatile it is) the colder the surrounding area will become.

The probability of icing tends to increase with increasing petrol volatility; the eight months between September and April have been reported as the period that carburettor icing is most prevalent and this is when intermediate and winter grade, high volatility, petrol is employed to enhance cold starting [3, 123, 128].

4.4 Anti-icing fuel additives

In order to optimise the volatility of winter grade petrol without incurring carburettor icing many workers propose the use of anti-icing fuel additives [123, 129, 130, 131, 132]. A study of this area of research will provide important information about the mechanism of carburettor icing and the effect of fuels of different properties, such as those expected from blending with ethanol.

There are two fuel additive approaches to control carburettor icing:

- Surfactants
- Freeze point depressants (cryoscopic additives)

4.4.1 Surfactants

Surface active components are generally credited with wetting the carburettor surfaces producing a slippery film to which the ice cannot bond [122]. There are a number of objections to this theory. Firstly, carburettor throttle plates can become coated with a layer of sticky gum and yet the tendency towards carburettor idle icing of such vehicles is not modified. Secondly, it has been reported that some surface active fuel additives form a protective layer on carburettor surfaces but again there is evidence to show that the tendency for these vehicles to suffer carburettor icing is not affected [124, 132].

Emelyanov *et al* studied the effect of surfactants on the structure of ice formed within the carburettor [132]. It was noted that if a surfactant fuel additive was not present, the ice crystals formed were star shaped or in the form of elongated plates, which would adhere to each other. With the surfactant fuel additive present the ice crystals were needle shaped. Due to their shape they could not adhere to each other and hence the rate of ice build up was low.

4.4.2 Freeze point depressants

Freeze point depressants are normally low molecular weight, water soluble molecules such as glycols or alcohols, with typical examples being dipropylene glycol or isopropyl alcohol. The effectiveness of these additives can vary greatly, so that, for example, 2% isopropyl alcohol gives the same benefit as about 0.1 % dipropylene glycol. The chemical similarity of these types of molecules to ethanol should be noted.

It is generally proposed that these additives function by dissolving in the condensed water in the carburettor, thereby lowering its freezing point in a manner analogous to the use of anti freeze in a radiator [122, 124].

A different mechanism was proposed by Lykov *et al* who studied the effects on icing of the heavy residue from alcohol stills [131]. This study suggested that oxygen containing components are adsorbed onto the surface of microscopic water droplets preventing their aggregation. Secondly surface active components, in the alcohol residue, form mixed inverted micelles within the petrol, which solubilise particles of water without allowing them to aggregate. Finally as the petrol evaporates in the carburettor the surface active components from the heavy alcohol residue are concentrated, again preventing ice formation. The problem with this latter explanation is that most of the low molecular weight alcohols employed as anti-icing additives will contain very little if any of these surface active species.

4.5 The effect of ethanol as a petrol blending component on carburettor icing

The prevailing wisdom from industry textbooks is that methanol and ethanol are extremely effective freeze point depressants and if used as a blend component in petrol they will prevent carburettor icing [133].

The most active area of study identified by the current project is carburettor icing in aviation, where the safety implications associated with engine failure are considerably more critical (it is estimated that on average there are seven aviation accidents per year caused by engine induction tract icing [134]). This is particularly of interest as some piston-engined aircraft have gained approval to operate on motor petrol (mogas) instead of aviation petrol (avgas) as mogas is cheaper than avgas [135, 136, 137]. It is generally accepted that the higher, and less rigorously controlled vapour pressure of mogas relative to avgas will lead to increased incidents of carburettor icing. Mogas is manufactured for ground vehicles and its vapour pressure is optimised for the season in which it is being used, in fact the vapour pressure of mogas is changed four times a year. Table 4 shows typical vapour pressures for mogas for summer, spring, autumn and winter, the exact values alter with geological location, the values shown in the table are for Canada. The vapour pressure for avgas is also shown for comparison.

Fuel Grade	Allowable Vapour Pressure (kPa)
MOGAS	Summer 79 max Spring 86 max Autumn 97 max Winter 107 max
AVGAS	38 to 49

Table 5 Seasonal vapour pressure variations of MOGAS and AVGAS in Canada [138]

As an aircraft gains altitude the atmospheric pressure decreases, effectively increasing the evaporation rate of the fuel, akin to the process of vacuum distillation. The higher the vapour pressure of the fuel the quicker it will evaporate and cool the surroundings. It has been shown that aircraft carburettor temperatures can be 7 °C lower when operating on mogas compared to avgas, hence leading to the increased incidence of icing. As well as being more prone to carburettor icing mogas can also cause vapour lock in an aircrafts fuel system, hence aircraft operating on mogas are restricted to a maximum altitude of 6000 feet [139, 140].

Concern has been expressed that the presence of ethanol in motor petrol will lead to the risk of carburettor icing due to ethanol's higher latent heat of vaporisation [141] A review of internet user group forums relating to light aircraft has confirmed that mogas containing ethanol is widely regarded as causing carburettor icing in aircraft [142, 143]

This opinion is given some credibility, in the US at least, because much of the petrol containing ethanol is splash-blended at tanker terminals[144, 145, 146]. In this type of blending, normal petrol is blended with 10 % ethanol at the road tanker loading terminal just before being shipped to retail service stations. This type of blending results in a significant increase in the volatility of the petrol as the blend contains both ethanol and the higher volatility components of the original petrol, see Figure 3.

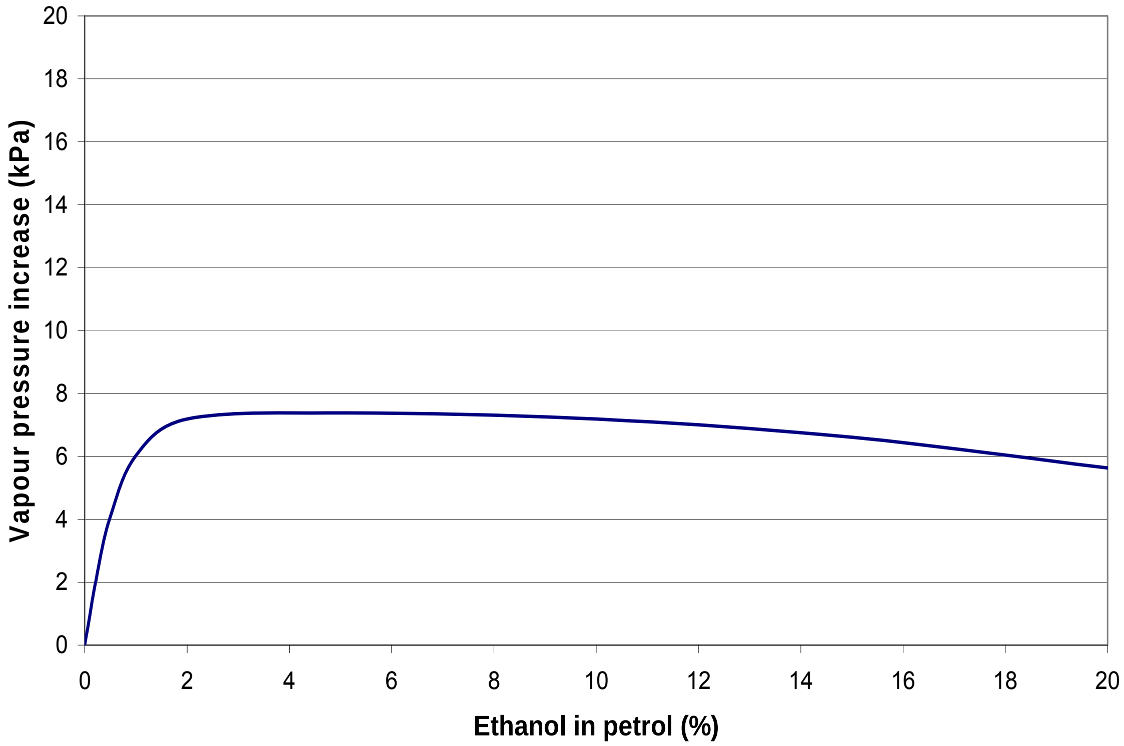

Figure 4 Variation of vapour pressure with ethanol content in petrol blend

A Federal waiver, sometimes called the 1 pound wavier, exists for conventional petrol splash blended with 10 % ethanol whose vapour pressure exceeds that of normal petrol by 1 pound (approximately 7 kPa) [147]. Furthermore, the splash blending is not always expertly conducted leading to the additional possibility of adding too much ethanol.

However in Europe, splash-blending is prohibited as a means of blending ethanol with petrol. Instead the ethanol is blended with 'Blendstock for oxygenate blending' (BOB) [148]. BOB is designed to have a lower vapour pressure than normal petrol, so that when the correct volume of ethanol is blended into the blend stock, the vapour pressure of the finished blend will not exceed the valve set down in BS EN 228 [3]. The vapour pressure of samples of mogas recently purchased in the UK has been reported [149] see Table 5. This clearly demonstrates that UK mogas is more volatile than avgas but ethanol blends are not more volatile than non-ethanol blends.

Date of purchase	Fuel type	Vapour pressure (kPa)	Ethanol content (%)
04.10.09	Avgas	41	0
07.10.09	Mogas	74	4.0
04.10.09	Mogas	69	2.9
27.10.09	Mogas	77	2.9
22.10.09	Mogas	68	0
24.10.09	Mogas	76	0
03.02.10	Mogas	72	0
03.03.10	Mogas	74	0

Table 6 Comparison of the vapour pressure of AVGAS, MOGAS and MOGAS/ethanol blends

Unfortunately this situation may change in the future as a proposed new version of BS EN 228 will allow a vapour pressure waiver for petrol containing ethanol [11].

It is noticeable that the internet forums that mention ethanol in mogas as causing carburettor icing in aircraft do not present any evidence to support this theory, other than sometimes quoting the high latent heat of vaporisation argument. E85 (mogas containing 85 % ethanol) is advertised as preventing carburettor icing in aircraft [150]. If the high latent heat of vaporisation of ethanol was responsible for carburettor icing then E85 would have a greater tendency to cause icing than mogas.

The anti icing properties of alcohol in aviation fuel have been recognised and reported [151, 152].

It should be noted that mogas containing ethanol is banned from use in aircraft [138, 139, 151, 152]. This is due to concerns regarding material compatibility and phase separation, carburettor icing is not mentioned.

Finally, a review of motorcycle related internet forums reveals that a much quoted cure for motorcycle carburettor icing is addition of ethanol to the petrol [156, 154, 155, 156].

4.6 OEM comments

Information regarding carburettor icing have been sought from the Motorcycle Industry Association (MCIA) and all the major importers and marketers of powered two wheeled vehicles.

The MCIA reported that carburettor icing was an issue during the mid 1980s when there was a step change in petrol formulation but is unaware of any current problems [101].

Triumph have no carburettor or throttle body icing issues and have not heard of any problems with their or competitor machines for at least a decade. A typical useful life of a motorcycle is in the order of ten years or 30 000 miles [102].

Harley Davidson did have some carburettor icing issues, not related to ethanol use, over four years ago but these were mostly cured by employing a fuel additive. The fuel systems of Harley-Davidson motorcycles were switched to fuel injection about four years ago [157].

Kawasaki are unaware of any carburettor or throttle body icing issues with their products [158].

A major manufacturer of carburettors has heard no recent reports of carburettor icing [23].

No OEM has been able to provide evidence of ethanol causing carburettor icing [159, 160] .

4.7 Extent of the problem

Ethanol is a well known anti icing fuel additive. There does not appear to be any induction system icing issues associated with its introduction at 5 % or increased usage at 10 %.

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5 The effect of petrol ethanol blends on microbiological contamination

5.1 Why is microbiological contamination important

Microbiological Contamination (MBC) can have serious adverse effects on the fuel system. MBC needs free water and fuel to grow. If water is allowed to collect in tank bottoms etc, the MBC will grow at the fuel water interface forming a mat or film similar in appearance to slime. This can lead to the following adverse effects:

- If disturbed some of the mat can become detached and block fuel filters or if the filter pores are too coarse, pass through and block vehicle fuel lines or vehicle fuel injectors.
- Corrosion of the fuel system. There are several pathways for this to occur:
    - Sulphate reducing bacteria (SRB) produce hydrogen sulphide which is very corrosive and can cause severe pitting of metal storage tanks.
    - Metabolic by-products of the MBC can create an electro-potential gradient which can corrode metal.
    - Metabolic by-products can also react with inorganic chlorates and chlorides producing acidic species that can degrade some plastics, metal oxide films and rubber.
    - Metabolic by-products can also increase the entrainment of water in the fuel leading to corrosion.
- MBC can lead to deterioration of fuel quality due to contamination by metabolic by products and utilisation of some of the fuel by the MBC. However this would take quite a long time as the fuel water interface represents only a small proportion of the bulk fuel.

5.2 Potential impact of ethanol on MBC growth.

There are two factors that suggest bio-ethanol may cause an increase in MBC viz:

- Hydroscopic properties - ethanol blends can contain very much more dissolved water than petroleum petrol and may therefore inhibit MBC growth as MBC requires free water to grow. However, if an ethanol blend containing dissolved water is blended with petrol (E0), or if the temperature of the fuel drops, the dissolved water may fall out of solution creating an environment suitable for MBC growth.
- Hydrocarbon composition - as ethanol comprises simple carbon chains incorporating oxygen it is more readily metabolised by micro-organisms that normally break down more complex molecules in petroleum petrol. This means that ethanol blends may provide a better source of nutrients for MBC growth than petroleum petrol.

5.3 Effect of E10 blends on MBC

A literature review by the Energy Institute [161] concluded that bio-ethanol present in petrol and it degradation products could provide a source of carbon for many micro-organisms. However if the ethanol portioned into a free water phase and is present at antimicrobial levels (> 5 % for most micro-organisms) then the susceptibility of ethanol based fuel to biodegradation was likely to be reduced.

5.3.1 Laboratory study to determine the effect of ethanol petrol blends on MBC growth

The objective of this study was to determine if ethanol petrol blends could promote MBC growth to a greater extend that purely hydrocarbon blends.

The base petrol for the study was a reference petrol RF 04 03 which was blended with E85 to produce the required test fuels. MBC has difficulty growing in petrol and it is unusual to find MBC in petrol. Limited time prevented the sourcing of MBC from petrol hence the MBC was obtained from samples grown from various diesel fuel sources.

Each test fuel was inoculated with MBC and treated with Parberry and Thistlewaite nutrient solution.

The diesel control was to demonstrate MBC would grow in diesel fuel.

After three weeks the diesel sample was exhibiting heavy MBC, however even after five weeks incubation the petrol samples still had not developed any MBC and at this point the study was terminated. It would appear that the MBC used was unable to grow in petrol and so very little can be concluded, although it does appear that the presence of ethanol does not significantly encourage the growth of MBC.

6 Conclusions

6.1 Fuel System compatibility

6.1.1 Vehicle problems resulting from the introduction of E10

Based on the experience of other markets where E10 has been introduced it is estimated that the majority of vehicles ten years old or older will not be compatible with E10 due to fuel system material incompatibility issues.

Field experience, vehicle trials and laboratory testing have demonstrated carburettor vehicles and powered two wheelers will suffer problems due to material incompatibility, corrosion and drivability problems.

Field experience has demonstrated first generation spark ignition direct injection vehicles are not compatible with E10 due to fuel system material incompatibility issues.

Field experience has demonstrated that vehicles and petrol fuelled equipment fitted with glass fibre fuel tanks may suffer catastrophic failure due to the incompatibility of the glass fibre resin with petrol ethanol blends. In addition to vehicles considered here, this could affect other applications not directly considered by this report, such as lawn mowers and pleasure craft.

Some documents do exist that have limited lists of vehicles compatible with E10 but if doubt exists the vehicle operator should contact the vehicle manufacturer for clarification.

Fuel filter blockage and reduced life of exhaust gas after treatment systems, the latter due to enleanment causing increased exhaust gas temperature, may be issues but this cannot be determined from the information gathered during this project. Vehicle trials and engine tests will be necessary to clarify the situation.

6.2 Carburettor icing

The findings of this study suggest the introduction of E10 will not result in a fuel that is more susceptible to causing carburettor icing.

6.3 Number of vehicles affected

Based on vehicle age, approximately 8.6 million vehicles will be unable to run on E10. Additionally some thousands of relatively new first generation SIDI vehicles and powered two wheelers will be unable to run on E10. A more exact estimation is not possible based on information available.

Based on an average vehicle life of 13 years very approximately half these vehicles will still be in use when the proposed phase out of E5 takes place in 2013.

7 Recommendations

Vehicles ten years old or older, carburettored vehicles (including powered two wheelers) and first generation direct injection spark ignition vehicles should not be fuelled on E10 unless the manufacturer can state the vehicles are compatible with E10.

The automotive industry should produce a comprehensive list of vehicles compatible with E10. While it is acknowledged that some lists do already exist if in doubt the vehicle operator should seek clarification from the vehicle manufacturer.

E5 should not be phased out in 2013, its widespread availability should continue for the foreseeable future.

Consideration should be given to maintaining a specification for E0 fuel for historic and vintage vehicles.

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Abstract

This document represents the final report of work performed under the Department for Transport (DfT) project "Assessing compatibility of fuel systems with bio-ethanol and risk of carburettor icing", tasked through AEA warrant number 14717211. This final report, due on the 29th October 2010, satisfies Deliverable 4 of the project, and updates and expand upon the interim summary provided by email on 26th March 2010, the first and second quarterly progress reports submitted on the 30th April 2010 and the 30th June 2010, the second milestone report issued on the 30th July 2010 and the draft final report issued on the 30th September 2010.

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