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High Octane Synthetic Gasoline

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Abstract

The subject of this study is a fuel formulation intended for vehicles comprising a spark-ignition engine (or gasoline engine), which has advantageous properties especially in competition (racing) vehicles requiring sufficiently high octane numbers to avoid knocking phenomena. The fuel is fully composed of synthetic components complying with the definition of advanced sustainable components according to the current FIA regulation and exhibits a reduction in greenhouse gas emissions of at least 70%. The fuel is predominantly composed of a synthetic hydrocarbon mixture and ethers commonly used in gasoline formulations (MTBE and/or ETBE). While the content of the first component is 50 - 60% m/m, the content of the ethers is 40 - 50% m/m. The fuel thus has more than two times higher oxygen content than standard market gasoline, which might require special adjustments of the fuel system and operational conditions.

Keywords

High-Octane, Synthetic Fuel, Sustainable Fuel, Racing Gasoline, Highly Oxygenated Gasoline

1. Introduction

Gasoline fuels marketed in Europe and complying with the EN 228 standard have a motor octane number (MON) greater than 85 and a research octane number (RON) of a minimum of 95 [1]. These fuels are suitable for the vast majority of automotive engines, but do not have octane numbers high enough to satisfy the requirements of competition vehicles. In order to increase their efficiency, modern spark-ignition engines tend to operate with increasingly high compression ratios, *i.e.*, with a high compression ratio applied to the fuel/air mixture in the engine before ignition. However, increasing the volumetric compression ratio in an engine increases the risks of abnormal knock-type combustion, generated by local self-ignition of the fuel mixture upstream of the flame front. This phenomenon creates a characteristic noise and is likely to damage the engine. For very high-power engines, such as motor racing vehicle engines, a high volumetric compression ratio is particularly desired. For this type of engine, it is therefore essential to use fuels with a high resistance to knocking and pre-ignition, thus resulting in fuels with the highest possible RON. If the octane numbers are insufficient, the phenomenon of knocking or self-ignition of the fuel is likely to appear, which can significantly reduce engine performance and even seriously damage it.

Moreover, for all vehicles intended for both consumer and competition applications, there is an increasing attempt to use fuels formulated from bases of renewable origin, and in particular so-called "biosourced" bases, in order to meet environmental concerns and to limit the use of fossil resources. Thus, current environmental concerns are pushing consumers to seek more environmentally friendly fuels. However, the use of fuel compositions from bio-sourced bases must not be to the detriment of fuel performance, and in particular, the octane number and engine power, which must be maintained or even increased. The most commonly used gasoline fuels with a high content of biocompounds are fuels comprising bioethanol, such as E85 fuels. Nevertheless, the use of these fuels represents a small part of the current automobile market. It is known to mix bioethanol with a petrol fuel of the SP95 type. The ethanol content is then limited to a maximum of 10% V/V in order to comply with the specifications of standard EN 228, in particular with regard to the incorporation of oxygenated compounds [1]. There is therefore a need to develop new fuel compositions intended to supply spark-ignition engines which make it possible to meet the requirements of modern vehicles, whether intended for general public applications (light vehicles, heavy goods vehicles, "off-roads" that is to say non-road, etc.) or for competition. Thus, there is a need for fuels for controlled-ignition internal combustion engines which have a high octane number, and very particularly a high RON, and which make it possible to maximize the engine power of motor vehicles operating with a high compression ratio, especially competition vehicles. One objective of this study is therefore to improve the performance of gasoline fuel compositions, in particular but not limited to fuel compositions intended for competition vehicles. There is also a growing need to be able to formulate such compositions from bases and/or compounds of renewable origin, also called biobased compounds.

As is well known in the prior art, octane-enhancing additives (or octane boosters) are typically added to gasoline-type fuel compositions. Organometallic compounds, including in particular iron, lead, or manganese, are well-known octane improvers. Thus, tetraethyl lead (TEL) has been widely used as a very effective octane improver. However, in most parts of the world, TEL and other organometallic compounds can now only be used in fuels in very small amounts, if at all, as they can be toxic, damage engines, and are harmful to the environment. Non-metal-based octane improvers include oxygenates (e.g., ethers and alcohols) and aromatic amines. However, these amines suffer from various disadvantages. For example, N-methylaniline (NMA), an aromatic amine, must be used at a relatively high treat rate (1.5 to 2% m/m additive/fuel base weight) to have a significant effect on the fuel octane rating. NMA can also be toxic.

Thus, fuel compositions with good intrinsic properties, *i.e.*, without the need to use organometallic or nitrogen-based octane boosters, and with high concentrations of fossil-free components are sought. Utilization of synthetic hydrocarbons (of non-fossil origin) and alcohols and/or ethers derived from non-fossil sources is a way with good potential to reach this goal [2] [3].

2. Results and Discussion

2.1. High Octane Synthetic Fuel Formulation

At the end of 2020, the FIA (Fédération Internationale de l'Automobile) published an invitation for a tender to select an exclusive fuel supplier for the World Rally Championship (WRC) for the 2022-2024 seasons. A new fuel specification was part of this invitation. While the high intention of this specification was to select a fuel with a high proportion of renewable components, the main difference (in comparison with the standard FIA gasoline specification—Appendix J, Article 252.9.1) from a fuel technical characteristics point of view was an increase in the allowed oxygen content [4]. This change can be predominantly associated with the intention to allow a higher content of high-octane oxygenates (with the potential to be derived from renewable sources) to maintain the knocking resistance of the fuel at the level required for high-performance competition vehicles (RON close to 102, MON close to 90). While the original oxygen level in the mentioned WRC fuel tender specification was 7.0% m/m, it was consequently increased to 7.5% m/m and was implemented in the new FIA advanced sustainable fuel regulation (Appendix J—Article 9.3.2). This value is more than two times higher than the oxygen content of the standard FIA gasoline specification (3.7% m/m) and many other regional fuel specifications (Europe, Japan, USA, etc.). Since not many fuel specifications/regulations allow such high oxygen content, this change forced the fuel suppliers to develop a completely new fuel, especially hand in hand with the intention to use a high proportion of the advanced sustainable (AS) components. By definition (FIA, Appendix J—Article 9.3.1), the AS components are those that are certified to have been derived from a renewable feedstock of non-biological origin (for example, a RFNBO), municipal waste, or non-food biomass [4]. While at least some oxygenates commonly used in fuel formulations, *i.e.*, alcohols and ethers, are/can be derived in a sustainable manner, the production of sustainable hydrocarbons in the gasoline boiling range is still highly limited. Moreover, the octane rating of the available advanced sustainable hydrocarbon-based components is relatively low and prevents their direct utilization even as standard market gasoline without octane rating enhancement by oxygenates or additives. The innovative fuel composition was thus a blend of a sustainable hydrocarbon mixture and oxygenates while maximizing the latter one in order to increase the octane rating of the first one. Since alcohols like methanol and ethanol have very high oxygen content, their potentially usable concentration is relatively low (up to 20% V/V) and not high enough to reach a RON above 100. The utilization of other oxygenates with lower oxygen content (higher alcohols and/or ethers) was thus the preferable way to reach the target octane rating of 101 - 102. Since the availability of the higher alcohols in the advanced sustainable form was also very limited, ethers were selected as the main group of oxygenates for the fuel compliant with the WRC/FIA specification.

The subject of the original fuel formulation development was thus a fuel composition comprising:

(i) 60 - 70% m/m of a synthetic hydrocarbon mixture comprising:

a) 40- 50% m/m of aromatic compounds;

b) 35 - 45% m/m of non-cyclic paraffins containing at least 4 carbon atoms and

c) 5 - 15% m/m of naphthenes;

(ii) 1 - 5% m/m of one or more alcohols;

(iii) 30 - 40% m/m of one or more ethers; and

(iv) 0.2 - 0.4% m/m of an additive package.

Although the performance of the fuel defined above was at the same level as previously used fuels predominantly composed of fossil-based components (including RON 101 - 102), there were several drawbacks requiring adjustments of the fuel system and an increase in the frequency of the engine oil exchange. The utilized hydrocarbon mixture contained an unusually high portion of heavy aromatic hydrocarbons (with 10 or more carbon atoms). It was found that although the fuel was fully compliant with the regulation, the presence of a high amount of heavy hydrocarbons significantly increased the fuel's propensity for oil dilution, especially during high loads of the competition vehicles' high-performance engines. The presence of the heavy aromatic hydrocarbons (with a boiling point of 180˚C and higher) in the used engine oils was then confirmed by gas chromatographic analysis. The main issue related to the oil dilution is the decrease of the engine oil's viscosity and thus lubricity, which can cause engine failure [5]. The rate of the oil dilution was dependent on the engine oil type/brand, engine load, and other operational conditions. The observed oil dilution usually reached 20 - 30% m/m during one competition section, which included 100 - 150 km at high load and 200 - 300 km at normal load. The kinematic viscosity of the oil decreased by 60 - 70% (at 40˚C) and 45 - 55% (at 100˚C). In order to overcome the issue without changing the fuel composition, several options were examined. Except for increasing the frequency of the engine oil change, utilization of a higher viscosity grade engine oil and/or utilization of ester-based engine oil (instead of hydrocarbon-based engine oil) provided positive results.

Another drawback of the presented fuel composition was the higher propensity for swelling of polymer-based fuel system materials. This can be associated with the increased content of oxygenated components, which are known to be more aggressive toward the mentioned materials [6]. The highest swelling rate during both the long-term test (36 days at ambient temperature) and the faster test (8 hours at 60˚C) was observed for FKM-based materials (size increase above 10% and volume increase even above 50%). An approximately two times lower swelling rate was observed with BF750-based material. The best results (lowest swelling rate) were reached with FFKM materials and Teflon. This issue with material compatibility was thus eliminated by the replacement of the less resistant materials with parts composed of Teflon or FFKM.

2.2. Innovative High-Octane Synthetic Fuel Formulation

Although the adaptation of the competition vehicles for utilization of the fuel composition described above was relatively successful, it was necessary to modify the fuel composition because the FIA regulation for advanced sustainable fuels (Appendix J—Article 9.3.2) was changed. The change in the regulation was based on the addition of two parameters (E120 and E135) of the standard distillation curve test (ISO 3405/ASTM D86) and modification of the limits of the parameter E150 of this test [2]. The main intention was to reduce the content of heavy compounds and thus reduce the engine oil dilution rate caused by them.

The reduction of the content of the heavy compounds was achieved by reducing the final boiling point (FBP) during the manufacturing process of the hydrocarbon mixture. While the original value of the FBP was ca. 205˚C, a fraction with an FBP of 195˚C was obtained during the initial experiments. Although some heavy aromatic hydrocarbons were removed by this step, it was not sufficient for a significant reduction of the oil dilution rate. The FBP of the original hydrocarbon mixture was thus reduced to 185˚C. This helped to reduce the content of C_{10} aromatics and almost completely eliminate the presence of C_{11+} aromatics. Although this modification led to a decrease in the octane rating of this component, it was a crucial step for the reduction of the oil dilution phenomenon. The obtained innovative hydrocarbon mixture was then utilized as a component in the formulation of the new WRC fuel, which was also compliant with the updated version of the FIA regulation. Except for the replacement of the originally used hydrocarbon mixture with a high content of heavy compounds by the mixture with a lower final boiling point, the formulation of the fuel was modified even further. Since the originally used combination of alcohol and ether was considered responsible for enhancing the fuel aggressivity toward polymer-based materials, the alcohol was removed from the formulation. This allowed the use of more ether than in the original formulation, which helped to maintain the octane numbers close to the target values.

The last modification of the fuel formulation was based on the utilization of the innovative additive package, which provides the same or even better features while using a significantly lower treat rate.

The subject of the innovative fuel formulation development is therefore a fuel composition comprising:

(i) 50 - 60% m/m of a synthetic hydrocarbon mixture comprising:

a) 35 - 45% m/m of aromatic compounds;

b) 40 - 50% m/m of non-cyclic paraffins containing at least 4 carbon atoms; and

c) 5 - 15% m/m of naphthenes;

(ii) 40 - 50% m/m of one or more ethers (preferably MTBE and/or ETBE); and

(iii) 0.1 - 0.2% m/m of an additive package.

These compositions have high RON (100 - 102) and MON (89 - 90) and are intended for spark-ignition engines (or gasoline engines). In applications in which the fuel flow rate is capped, particularly in the case of competition vehicles, the use of the composition according to the description mentioned above makes it possible to achieve higher engine power levels at a constant fuel flow rate. In particular, the formulation of a composition with the compounds and in the specific proportions defined above has proven to enable synergistic performances in terms of octane number RON, net calorific value, and engine power.

In comparison with the original version of the fuel, the propensity for oil dilution and swelling of the polymer-based fuel system materials has been reduced. The oil dilution rate was reduced by 15 - 20%, which means that the propensity is still quite high and further improvements of the fuel formulation would be necessary to reduce the oil dilution rate even more. On the other hand, the tendency for swelling of the polymers was reduced more significantly, so the observed dimensions' increase of all tested materials (including FKM) was below 10%.

This fuel composition can advantageously be, in whole or in part, prepared from bases and/or compounds of renewable origin, for example, of plant origin. In particular, the fuel composition may contain at least 60% m/m of one or more biobased components, preferably at least 65% m/m, more preferentially at least 70% m/m and better still at least 75% m/m in bulk of one or more biosourced bases. Thus, it makes it possible to substantially reduce greenhouse gas emissions, determined in accordance with EU Directive 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy produced from renewable sources. The reduction in greenhouse gas emissions obtained by means of the fuel composition described above is at least 60%, compared to the reference fossil fuel defined in this Directive.

2.3. Detailed Description of the Fuel Composition

The fuel composition contains a mixture of hydrocarbons comprising: a) 35 - 45% m/m of aromatic compounds; b) 40 - 50% m/m of non-cyclic paraffins containing at least 4 carbon atoms; and c) 5 - 15% m/m of naphthenes.

The aromatic compound(s) are preferably chosen from alkylbenzenes comprising from 7 to 10 carbon atoms. Preferably, the content of the aromatic compounds ranges from 35 to 45% m/m, preferably from 35 to 40% m/m, relative to the mass of the mixture of hydrocarbons.

The fuel also contains non-cyclic paraffins containing at least 4 carbon atoms. By "paraffins" is meant, in a manner known, branched alkanes (also called iso-paraffins or iso-alkanes) and unbranched alkanes (also called n-paraffins or n-alkanes). The mixture of hydrocarbons advantageously contains from 7 to 12%

m/m of n-paraffins and from 30 to 40% m/m of iso-paraffins. Preferably, the content of paraffins ranges from 40 to 50% m/m, more preferably from 40 to 45% m/m, relative to the mass of the mixture of hydrocarbons.

The fuel also contains naphthenes. By "naphthenes" is meant cyclic alkanes (or cycloalkanes). Preferably, the naphthenes are chosen from cyclic alkanes containing from 5 to 10 carbon atoms, and more preferably from 6 to 9 carbon atoms. Preferably, the content of naphthenes ranges from 5 to 10% m/m, more preferably from 5 to 8% m/m, relative to the mass of the mixture of hydrocarbons.

According to a preferred embodiment, the fuel composition comprises at most 2.5% m/m of olefins, preferably up to 2% m/m of olefins.

The utilized mixture of hydrocarbons comes from plant-based raw materials. Thus, the mixture advantageously consists entirely of biosourced hydrocarbons. The plant-based raw materials may for example be chosen from cereals (for example wheat, maize), rapeseed, sunflower, soya, palm oil, sugar cane, beet, waste wood, straw, bagasse, grape marc, used vegetable cooking oils, seaweed, and lignocellulosic materials. Particular preference is given to vegetable raw materials containing carbohydrates, such as cereals, sugar cane, beets, wood waste, straw, bagasse, grape marc, and lignocellulosic materials which may be derived from the timber industry. Preferably, so-called second-generation (2G) or advanced plant material is used, in particular plant material that is not in competition with the food resource. The mixture of hydrocarbons is preferably obtained by converting the plant material into alcohols containing 1 to 5 carbon atoms, preferably methanol and/or ethanol, which are converted into hydrocarbons in the presence of catalysts making it possible to dehydrate the alcohols and produce reaction intermediates which, catalytically, are then transformed into hydrocarbons.

The fuel formulation also contains at least one ether. Ethers, also called ether-oxides or alkoxy-alkyls, are compounds of formula R-O-R', in which R and R', identical or different, represent an alkyl radical. Preferably, the oxygenated compound(s) are chosen from tert-butyl methyl ether (MTBE), tert-butyl ethyl ether (ETBE), tert-amyl methyl ether (TAME), tert-amyl ethyl ether (TAEE), and mixtures of these compounds. According to a preferred embodiment, one or more ethers of plant-based origin, or bioethers, are used. The ether can be obtained in a renewable manner by using, for example, a renewable alcohol and an olefin resulting from thermal or catalytic cracking or by steam cracking of a renewable charge. Bioethers can, for example, be produced by reaction between an alcohol and a generally branched olefin. They can be produced from renewable raw materials (in particular, vegetable raw materials) by using, for example, alcohols obtained by transformation (for example, fermentation) of renewable raw materials and olefins resulting from cracking (thermal cracking, catalytic, or steam cracking) of a renewable charge or by dehydration of an alcohol. Preferably, the olefins are produced by steam cracking of bionaphtha, which is a by-product resulting from the production of renewable diesel by deoxygenation and isomerization of triglycerides of plant origin. The composition has a total content of ether(s) ranging from 40 to 50% m/m, preferably from 40 to 45% m/m, relative to the total mass of the fuel composition.

The fuel formulation may also contain one or more alcohols, preferably chosen from C_1 to C_6 alcohols, more preferably from C_1 to C_4 alcohols. Mention may in particular be made of methanol, ethanol, and isopropanol. Methanol and ethanol are particularly preferred. According to a preferred embodiment, alcohols from renewable raw materials, and in particular of plant origin, also called bioalcohols, are used. Such alcohols may be present in the fuel formulation in a content ranging from 0 to 2% m/m, preferably from 0 to 1% m/m.

In addition to the base compounds described above, the fuel formulation also comprises one or more additives, chosen from among those usually employed in gasoline fuels. In particular, the fuel formulation comprises at least one detergent additive ensuring the cleanliness of the engine. The composition may also comprise at least one lubricity additive or anti-wear agent. Other additives may also be incorporated into the fuel formulation, such as anti-recession valve additives, antioxidant additives, and additives increasing the octane number, in particular chosen from amines, preferably aromatic, with or without oxygen. The additives described above can be added to the fuel composition in an amount ranging, for each of them, from 10 to 5000 ppm by mass, preferably from 50 to 1000 ppm by mass and better still from 100 to 500 ppm by mass, based on the total mass of the fuel composition. According to a preferred embodiment, the composition comprises at least one additive, advantageously chosen from detergent additives, lubricity additives, anti-recession valve additives, antioxidant additives, additives increasing the octane number, and mixtures of such additives. The fuel compositions have a lead content generally less than or equal to 5 mg/L (present, for example, in the form of tetraethyl lead) and, preferably, are lead-free, that is to say they do not contain lead or compounds containing lead. They are also free of sulfur (maximum content of 10 ppm by weight).

The composition as described above generally has a research octane number (RON index) greater than or equal to 98, preferably greater than or equal to 99, and more preferably greater than or equal to 100, the RON being measured according to the standard ASTM D2699-21 (or more recent). The values above relate to the intrinsic octane number of the composition, that is to say without the addition of additional compounds such as octane booster additives.

2.4. Utilization of the Innovative High-Octane Synthetic Fuel

The composition described above is intended for supplying a spark-ignition engine. The engine can be of the direct injection or indirect injection type. The fuel composition can be advantageously used to supply a high-efficiency, high-power spark-ignition engine, such as a competition vehicle engine. It may be in particular an atmospheric or turbocharged engine used in a competition vehicle (circuits or rallies), or even a hybrid engine, that is to say a heat engine coupled to an electric motor.

At the same time, the fuel with the composition described above can be used for reducing greenhouse gas emissions, as determined in accordance with EU Directive 2018/2001 of the European Parliament and of the Council of December 1, 2018 on the promotion of the use of energy produced from renewable sources. According to this Directive, the reduction of greenhouse gas emissions is determined in relation to a reference fossil fuel. The method for calculating the reduction percentage is more specifically defined in Annex V, Part C of the Directive.

The reduction in greenhouse gas emissions obtained by means of the fuel composition of the invention is at least 60%, preferably at least 65%, and even more preferably at least 70%, compared to the reference fossil fuel defined in the Directive.

3. Conclusions

The innovative fuel formulation described above was developed as a substitute for FossilFree100 WRC fuel, which was predominantly used in the World Rally Championship (WRC) from 2022/01 to 2024/03. The innovative fuel formulation was then used in the WRC from 2024/04 to 2025/03. The changes in the fuel formulation can be summarized as follows:

- Replacement of the utilized base synthetic hydrocarbon mixture by a new version containing fewer of the heavy compounds reduces the oil dilution and soot formation tendencies.
- Modification of the concentrations and types of the utilized oxygenated compounds increases octane numbers and improves material compatibility with polymer-based fuel system components.
- Optimization of the concentration and composition of the utilized additive package.

The fuel is fully compliant with the FIA advanced fuel (AS Petrol) regulation (from 26.10.2025, Article 266, 3.2) listed in Appendix J of the FIA International Sporting Code. It is also composed of 100% advanced sustainable components and exhibits a GHG emissions reduction of at least 70%.

Main features of the fuel formulation:

- Utilization of a synthetic hydrocarbon mixture with a final boiling point of up to 185˚C containing 35 - 40% V/V of aromatic compounds and up to 4% V/V of olefins.
- Alcohol content below 1.0% V/V.
- Ether (MTBE and/or ETBE) content above 40% V/V.

Oxygen content of 7.3 - 7.5% m/m.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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