FUELS JOINT RESEARCH GROUP

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# Survey on Advanced Fuels for Advanced Engines

## Project Report

Funding by IEA Bioenergy Task 39

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## Contents

## Abbreviations

AFID ........................................................Alternative Fuels Infrastructure Directive
AFV ..............................................................................Alternative Fuel Vehicles
AMF ............................................................................... Advanced Motor Fuels
BEV ............................................................................. Battery Electric Vehicle
BtL.......................................................................................... Biomass to Liquid
BTX .........................................................Benzene, toluene and xylene isomers
CFPP.......................................................................... Cold Filter Plugging Point
CI......................................................................................... Compression Ignition
CN ............................................................................................... Cetane Number
CNG..............................................................................Compressed Natural Gas
CP.......................................................................................................Cloud Point
CPD ...........................................................Clean Power for Transport Directive
d/iLUC..........................................................direct/indirect Land Use Change
DME ................................................................................................ Dimethyl ether
DOC......................................................................... Diesel Oxidation Catalyst
DPF ..................................................................................Diesel Particle Filter
EGR ........................................................................... Exhaust Gas Recirculation
EPA.................................................................. Environmental Protection Agency
ETBE................................................................................. Ethyl Tert-Butyl Ether
ETD .......................................................................... Energy Taxation Directive
EV.................................................................................................. Electric Vehicle
EU ................................................................................................ European Union
FAME .................................................................................. Fatty Acid Methyl Ester
FCV................................................................................................ Fuel Cell Vehicle
FEV ............................................................................................ Full Electric Vehicle
FQD ........................................................................................ Fuel Quality Directive
FT ................................................................................................... Fischer-Tropsch
FT-IR..................................................Fourier Transformed Infrared Spectroscopy
FRL ................................................................................................ Fuel Readiness Level
GC/MS .................................................Gas Chromatography/Mass Spectroscopy
GHG ........................................................................................... Green House Gas
GTL................................................................................................... Gas to Liquid
HC ......................................................................................................Hydrocarbon
HCCI ..................................................Homogeneous Charge Compression Ignition
HDV........................................................................................ Heavy Duty Vehicle
HEFA .................................................... Hydroprocessed Esters and Fatty Acids
HVO ................................................................................Hydrotreated Vegetable Oils
IEA........................................................................... International Energy Agency
LBG................................................................................................ Liquefied Bio Gas
LBM.............................................................................. Liquefied Bio Methane
LCA.......................................................................................... Life Cycle Assessment
LCFS ........................................................................... Low Carbon Fuels Standard
LDV ........................................................................................ Light Duty Vehicle
LEV ....................................................................................... Low Emission Vehicle
LG.......................................................................................................... Liquid Gas
LNG ........................................................................................ Liquefied Natural Gas
LPG............................................................................... Liquefied Petroleum Gas
MDV...................................................................................... Medium Duty Vehicle
NM[V]HC...................................................... Non-Methane [Volatile] Hydrocarbons
MMT .................................... Methyl-cyclopentadienyl-Manganese-Tricarbonyl
MTBE ........................................................................ Methyl-Tert-Butylether

NMR ........................................................ Nuclear Magnetic Resonance spectroscopy
$NO_X$ ........................................................ Nitrogen Oxide
OEM ........................................................ Original Equipment Manufacturer
OME ........................................................ Oxymethylene dimethyl ether
PAC ........................................................ Polycyclic Aromatic Compounds
PAH ........................................................ Polycyclic Aromatic Hydrocarbons
PHEV ........................................................ Plug In Hybrid Electric Vehicle
PM ........................................................ Particle Mass
PN ........................................................ Particle Number
PtL ........................................................ Power to Liquid
R&D ........................................................ Research and Development
RE ........................................................ Renewable Energy
RED ........................................................ Renewable Energy Directive
RFS ........................................................ Renewable Fuels Standard
RETD ........................................................ Renewable Energy Technology Department
SCR ........................................................ Selective Catalytic Reduction
SI ........................................................ Spark Ignition
SimDis ........................................................ Simulated Distillation
SMG ........................................................ Saturated Monoglycerides
TCI ........................................................ Total Capital Investments
THC ........................................................ Total Hydrocarbons
TRL ........................................................ Technology Readiness Level
UCO ........................................................ Used Cooking Oil
ULSD ........................................................ Ultra Low Sulfur Diesel
VAT ........................................................ Value Added Tax
VRT ........................................................ Vehicle Registration Taxes
WHSC ........................................................ World Harmonized Stationary test Cycle
WTT ........................................................ Well-To-Tank
XTL ........................................................ X to Liquid
ZEV ........................................................ Zero Emission Vehicle

# Executive summary

The literature study “Survey on Advanced Fuels for Advanced Engines” has been set up as a review-like compilation and consolidation of relevant information concerning recent and upcoming advanced engine fuels for road vehicles with special focus on biomass-based liquid fuels. It is provided as a self-contained report, but at the same time serves as an updated and complementary resource to IEA-AMF’s online fuel information portal (http://www.iea-amf.org). An attempt is made to describe the *status quo* and perspectives of advanced fuels and to give a broad overview on parameters, tools and experimental approaches necessary for fuel characterization and evaluation. The focus of literature coverage, especially concerning fuel properties and exhaust emission research results, is from recent to approximately five or ten years back, but if appropriate, older resources were considered too in the general discussion of relevant effects and mechanisms.

Introductory Chapter 2 summarizes framework conditions for advanced fuel applications in terms of regulatory measures and incentives for sustainable and fair-trade action, climate change prevention and energy-efficient vehicle operation. Following these non-technical topics, Chapters 3 and 4 gives information about fuel standards and fuel properties, which should be considered when introducing new fuels. Chapter 5 provides tabulated information on feedstock, production schemes, costs and market issues for the main types of advanced biofuels considered in this study, i.e. hydrotreated vegetable oils (HVO/HEFA), biomass-to-liquid (BTL) fuels (i.e. paraffinic Fischer-Tropsch (FT)), methanol, dimethyl ether (DME), oxymethylene dimethyl ether (OME), lignocellulosic ethanol and liquefied biomethane. Also fuel properties and emission trends are shown in this chapter. Accordingly, biodiesel is explicitly included in subsequent discussions and complemented by an excursus on metathesis biodiesel.

Chapter 6 refers to reactivity and stability of fuels with regard to interactions among different fuel components and between fuel and engine oil. Deterioration of fuel and engine oil quality will affect long-term fuel storage and vehicle functionality by formation of deposits and sludge and is manifested by laboratory parameters not necessarily detectable macroscopically. Influencing factors like molecular structure, temperature, oxidizing agents, additives, impurities and metal catalysis are discussed according to published research results.

Chapter 7 deals with health effects of engine exhaust and to this end describes important gaseous and particulate constituents, their characterization and measurement. As specific exhaust species, regulated parameters CO, HC, $NO_X$ and unregulated components polycyclic aromatic hydrocarbons (PAH) and carbonylics are considered, and particular aspects of particle size, number and composition are discussed. Reference is made to formation of ozone and ambient aerosol as secondary impacts of engine exhaust. Short keynotes on research and review articles on issues of toxicology, mutagenicity and other adverse effects of engine exhaust are provided. A thorough introduction to dedicated engine emission testing and a literature survey on published emission measurement results using various engine types and fuels are given.

As a conclusion of the study, the diversity of fuels will increase in the future. New advanced fuels will be introduced in the market (e.g. HVO) or will become the focus of research activities (e.g. OME). One criterion for successful introduction of a new fuel in the market is that the new fuel can be used as a drop-in fuel. These fuels have the advantage that small amount of the fuel can be tested using existing infrastructure and engine techniques. In this phase of market introduction, reactions among fuel

components and material interactions can also be detected. At the moment, most research activity deals with the behavior of aging products of biodiesel in non-polar fuels like HVO/HEFA or X-to-liquid (XTL, FT fuels).

Introducing new fuels needing an adaption of the engine technique or a new engine concept in the market requires much more effort. Next to the new fuel, also a new infrastructure and new engines have to be developed and launched. This is only possible if fuel and automotive industries, politics and broad public support the new development.

Another key factor for advanced fuel is the raw material base. The production of advanced fuels should be independent of fossil resources. Therefore, biomass or renewable electrical power (e.g. wind power or solar energy) must be the source of advanced fuels. Biomass is intensively used by first generation biofuels, but there is a potential to raise the share of renewable fuel with the introduction of advanced fuels having a broader base of biomass. Electric power as an energy source for advanced fuels also will become interesting, if the share of renewable electricity in the grid will increase. Nevertheless, already today research is necessary to have the technique(s) ready in time.

Last but not least, for further development of engine technique, advanced fuels can be use as construction or design element. If it is possible to optimize the burning process and to minimize emissions by the use of advanced fuels, new vehicles can have a better performance at the same price.

In summary, advantages and disadvantages of the considered advanced fuels are listed in Table 1. From today's point of view, no advanced fuel has the potential to fully replace fossil fuel use in the near or middle future, but all advanced fuel options have the potential reduce fossil fuels usage significantly.

Table 1: Advantages and disadvantages for the market introduction of advanced fuels (++ clear positive impact, + slight positive impact, 0 no impact, - slight negative impact, -- clear negative impact)

| Fuel | Production technique | Raw material base | Drop-In fuel | Engine technique | Exhaust gas emissions |
|---|---|---|---|---|---|
| **HVO** | ++ | + | ++ | ++ | + |
| **BTL** | 0 | +/++ | ++ | ++ | + |
| **DME** | 0/++ | methanol | -- | 0 | ++ |
| **OME** | -- | methanol | 0 | 0 | ++ |
| **Methanol** | 0/++ | +/++ | - | 0 | 0 |
| **Lignocellulosic ethanol** | + | +/++ | + | + | + |
| **Bio-LNG/LBM** | ++ | + | ++ | ++ | 0 (++)* |

*compared to fossil methane (to gasoline)

# 1 Introduction

## 1.1 Background and motivation

The long history of technical evolution of combustion engines and appropriate fuels has seen many adaptations and refinements that underline the close interrelation of engine and fuel development. Operation of engines by applying "whatever may serve as combustive fuel" is an outdated concept, since modern engines are highly sophisticated instruments requiring clean, well-specified operating fluids as fuels. The fuel requirement mutates from the former simple energy carrier to a future key constructional element for combustion engines.

Today's road transport still almost completely relies on vehicles powered by combustion engines, with fossil fuels being the main energy carrier. The sheer dimension and ongoing increase of road traffic leads to large amounts of fossil fuels being burnt, coupled to corresponding pollutant emissions and consumption of resources and energy for fuel supply. The urgency of reversing negative trends of climate change and environmental pollution demands countermeasures that on one hand reduce fuel consumption in general and enhance engine efficiency in particular. On the other hand, a broader range of adverse emissions and unwanted effects associated with fuel supply and road traffic has to be controlled and minimized. To this end, it is necessary to improve engine design as well as to optimize fuel properties in terms of engine performance, sustainability and climate and environmental preservation.

Engineering efforts to cope with these technical challenges are embedded in general social and market requirements like security of energy supply, diversification of fuel sources to buffer against the instabilities of fossil fuel prices, consumer demands regarding vehicle performance, objections to vehicle concepts or compatibility of prospective alternative fuels, or objections to environmental footprints of biofuels, all under the industrial premise of cost-efficiency and competitiveness. Perception of environmental trends by the public and political implementation of corresponding regulatory measures strongly influence the margin or balance or prioritization for continuing existing technologies versus focusing on implementing new advanced technologies.

The remarkable progress achieved to date regarding engine and fuel issues has been accomplished by performing and evaluating an enormous number of engine tests and calibration experiments complemented by mathematical modeling. When referring to engine tests, we mean a single combination of combustion instrument (engine) and fuel. Results will change using a different engine or combustion apparatus, or by modifying driving or ambient conditions, and of course using a different fuel. It is therefore essential to refer to distinct engine-fuel combinations and to develop fuels and modern engines in a strongly coordinated manner. Specific engine performance (for a given fuel) implies specific exhaust gas components and consequently dictates the requirements for the exhaust gas aftertreatment strategy. Moreover, fuel chemistry is important for fuel-fuel and fuel-engine oil interactions, especially to functional chemical groups potentially present in the fuel that increase or decrease polarity or are susceptible to oxidation, like e.g. unsaturated carbon bonds. Undesired effects are formation of deposits in the fuel storage and supply system and sludge in the engine oil that can severely damage engines. Whether in neat form, as preformulated blend or as drop-in application, limited suitability of fuels for long-term storage in the fuel tank is a critical factor for plug-in hybrid electric vehicles (PHEV) that have low/infrequent fuel consumption and prolonged intervals between refillings. Emergency stand-by generators, seasonal vehicles and machinery with only sporadic use share these same issues and raise similar concerns.

A suite of advanced fuels including biofuels have emerged over the years whose production continues to be optimized with respect to sustainability, greenhouse gas mitigation, engine performance and exhaust gas quality. Broad acceptance of a new advanced fuel, meanwhile, depends on proper experimental and practical experience from engine/vehicle testing as well as reliable and sufficient supplies of such fuels to enable engine tests to be performed. Awareness of corresponding fuel properties both to experts and consumers is also a prerequisite for general acceptance, market entry and for focused research and development (R&D) to further optimize engine combustion.

Scientific knowledge on chemical species and inventories of vehicle pollutant emissions, underlying mechanisms and influencing factors has grown substantially over time, as has knowledge on pollutant effects on biota and ecosystems. In parallel, powerful techniques have been developed for detecting and monitoring relevant processes and chemical species over much of the lifecycle of fuels usage (transport and storage, combustion, exhaust treatment). Insights into factors influencing fuel chemistry, fuel stability and combustion behavior have helped to establish concepts for tailor-made fuels and quality criteria with respect to substance class composition and purity.

## 1.2 Objectives and structure of the study

To contribute to positive developments for the future use of especially advanced biofuels, a global survey on different types of biomass-derived fuels and their qualities is necessary; similar to what is provided by OEMs for fossil fuels. This knowledge is relevant to identify potential future problems, challenges and opportunities for state of the art and advanced engine technologies – independent of whether biofuels are used as oxygenates or blends, or as neat or drop-in fuels. A dedicated survey of the global situation on current and advanced biofuels options enables OEM and Tier1 suppliers to optimize their modern and advanced engine technologies in accordance with regulatory requirements.

Past experiences and lessons learned suggest that such a joint implementation of engines and fuels development might have been a mechanism for reducing concerns, obstacles and constraints from the automotive industry against the use of biofuels. With regard to the targets and objectives of IEA Bioenergy Task 39, this study contributes a survey on dedicated quality aspects of certain liquid biofuels with special regard to advanced biofuels. Due to the fact that biofuels face special sustainability concerns in terms of exacerbating possible fuel-food conflicts, land-use change and engine performance problems, a sound and valid data basis is essential to facilitate the discussion. To attain a comprehensive characterization of advanced fuels, these are considered from multiple perspectives: (i) with respect to fuel properties within the regulatory frame of fuel standards; (ii) by looking at possible unintended fuel reactions, interferences and resulting vehicle performance issues; and (iii) regarding health and other effects of engine emissions as well as factors that impact exhaust quality and proper measurement of emission data.

# 2 Non-technical framework for advanced biofuels

Impacts of road transport on global climate, environment and human health have become an increasingly important issue of public debate and political decision making where substantial technological progress is needed. It is well recognized that straightforward sustainability criteria such as greenhouse gas reduction, protection of valuable ecosystems and avoidance of food-fuel conflicts and promotion of fair-trade in general, are important goals to be achieved. Consequently, mandatory regulations and incentive measures have been implemented in order to make fuels and vehicles fulfill minimum requirements and stimulate necessary improvements with respect to criteria mentioned.

While this study focuses on modern engine fuels as the technical factor of key importance for clean and efficient engine operation, it is useful to examine the general regulatory framework concerning sustainable mobility. Therefore, we will introduce the subject of advanced fuels by providing a tabulated, summary overview of recent and near future (anticipated) policies, regulations and incentives for fuel supply and transport. This covers

- Political and legislative aspects on an international level;
- Current development of biofuel markets and forecast scenarios for different biofuels;
- Discussion of potentials and challenges of advanced fuels;
- Requirements with regard to sustainability criteria.

Fields of action and relevant factors that characterize the non-technical framework concerning fuel and vehicle regulation are shown in Figure 1.

Regarding technical aspects, increasingly restrictive regulatory measures have been implemented to limit the adverse effects of motor vehicle traffic. Corresponding regulations specify engines and vehicles, emissions from driving operation, physical-chemical properties of fuels and operating fluids as well as requirements for performing test procedures and laboratory analyses. These issues are discussed in Chapter 4 (Technical background of selected fuel properties) and Chapter 7 (Known health effects).