Spark versus compression ignition in a new energy environment

Could the development of new, more efficient engine technologies also help to address the diesel/gasoline supply imbalance?

Dieselisation of the fuel market is accelerating as commercial transport increases and as the fuel consumption of new passenger cars decreases. At the same time, the recent US revolution in shale gas and tight oil is putting new pressure on worldwide refining as more gasoline molecules are available from light crude extraction and from chemical feedstock substitution. From a renewable fuel perspective, ethanol and its derivatives are available in larger volumes.

As the world considers how to achieve best-in-class 'well to wheels' greenhouse gas reduction from transport, is it time to look at new opportunities to combine the highest efficiency engine technology with the lowest greenhouse gas (GHG)-emitting fuels? Would a low octane, low cetane gasoline or even a current pump gasoline be a better choice for future compression ignition engines?

Introduction

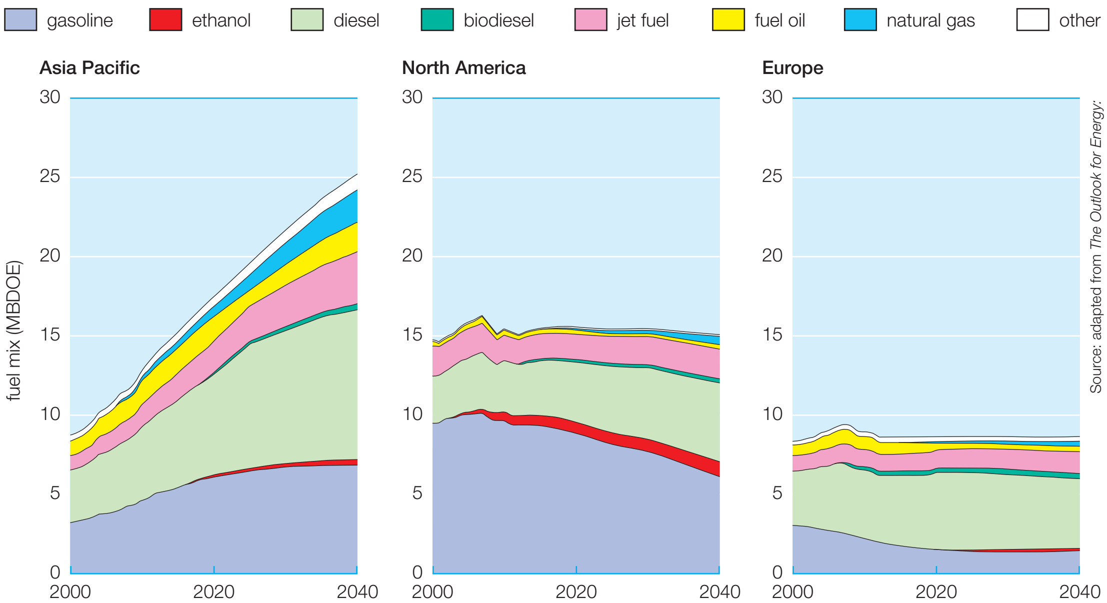
The overall world energy demand is evolving; demand is increasing in developing parts of the world, while in others, such as Europe and North America, it is declining. Looking more closely at transportation, as this is the sector that accounts for about 60% of oil demand today, it is clear that an understanding of the trend in overall fuel demand and the mix of fuel types over time is critical to ensuring that refinery operations and trade opportunities are effective in meeting the changing requirements of people around the world efficiently over time.

It is predicted that, in the period to 2040, the growth in demand for transportation will be led by the Asia Pacific region, and demand in North America and Europe will remain relatively flat while energy demand in Europe for light-duty vehicles is expected to decline by about 40%. Commercial transportation is likely to grow by about 20%, keeping energy demand for transportation stable.

Global diesel demand will increase by more than 75%, led by the Asia Pacific region, where demand for diesel will more than double. The demand for diesel fuel in North America will increase by about 60% even as the overall demand for transportation fuel remains relatively flat. In Europe, diesel volumes grow (+14% by 2025) and then decline (-11% from 2025–2040), remaining stable over the outlook period (+2% until 2040).

Global demand for gasoline will be relatively flat from 2010 to 2040, led by a decline in North America. Gasoline

Figure 1 Transportation fuel mix by region



Source: adapted from *The Outlook for Energy: A View to 2040* (Exxon Mobil, 2014).

demand declines due to improved light-duty fuel efficiency as well as increased use of oxygenates. In Europe, the demand for motor gasoline drops significantly (-32% by 2040). It is predicted that oil will remain the fuel of choice for transport in the coming decades, making up 89% of the transport fuel mix for Europe by 2040.

The demand for natural gas used for transportation is expected to grow by nearly 70%, with 60% of the growth in the Asia Pacific region and 15% in North America. Most of this growth comes from commercial transportation, such as liquefied natural gas (LNG) for long-haul trucks and compressed natural gas (CNG) fuelling local delivery fleets and buses.

The past few years has seen a boom in the production of natural gas in the USA, due to both continued production of conventional gas resources, as well as a surge in unconventional gas. In Pennsylvania, for example, the Department of Environmental Protection is reporting a 15x increase in natural gas production. In addition to this there has been an increase in tight oil production in some states, for example North Dakota. These trends are expected to continue.

Challenge to EU competitiveness

As a result, energy prices for US refineries have the advantage relative to those in Western Europe, as well as in the Asia Pacific region. Energy prices in Europe are currently much higher than in the USA, making it difficult for European businesses to compete on the global stage.

EU prices are twice as high for electricity, and three times as high for gas. This regional difference is expected to remain large through to 2035. Energy costs make up around 60% of European refineries' total operating costs, versus 28–30% for Eastern US refineries.

In addition, crude production growth worldwide is focused in the USA, Iran and Canada, with more modest growth in the Middle East and Western Africa, and essentially constant production in Europe. Taken together, Western European refiners are disadvantaged versus other global refiners in terms of energy prices, and crude availability.

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The diesel-gasoline imbalance is expected to increase into the foreseeable future.

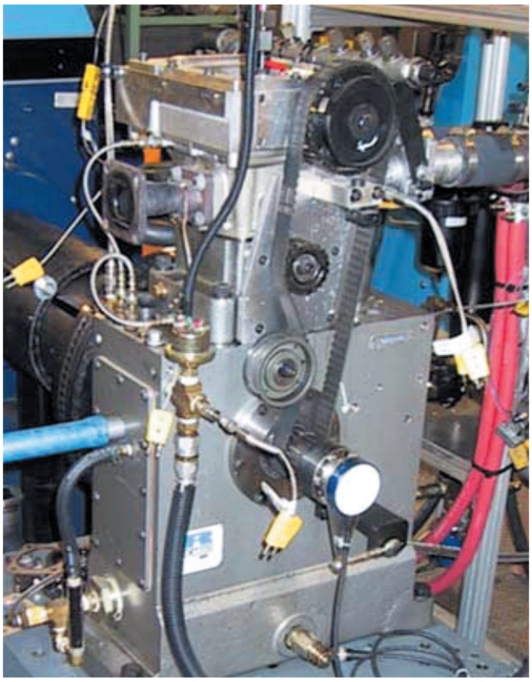
The increasing global diesel demand, the decreasing demand for gasoline and increasing availability of gasoline-type molecules from light crude extraction and chemical feedstock substitution, create a diesel-gasoline imbalance which is expected to increase as time goes on. These factors, as well as pressures to reduce GHG emissions, mean that refiners worldwide, and particularly those in Western Europe, are coming under increasing pressure.

Focus on vehicle efficiency

On the other hand, as pollutant emissions from motor vehicles continue to fall to meet lower regulated emission limits, attention is increasingly focused on vehicle efficiency and on fuel consumption to address future concerns with energy supplies and transport's contribution to GHG emissions. Engine, aftertreatment and vehicle technologies are evolving rapidly to respond to these challenges.

Considerable research is concentrating on improving the combustion performance of light-duty engines. Compared to spark ignition (SI) engines, compression ignition (CI) engines are already very efficient so the challenge is to maintain or improve CI engine efficiency while further reducing pollutant emissions. Engines using advanced combustion technologies are being developed that combine improved efficiency with lower engine-out emissions, thus reducing the demand on exhaust aftertreatment systems and, potentially, vehicle costs. Because these concepts combine features of both SI and CI combustion, the optimum fuel characteristics could be quite different from those needed by today's conventional gasoline and diesel engines.

In general, these advanced combustion concepts substantially homogenize the fuel-air mixture before combusting the fuel under low-temperature combustion (LTC) conditions without spark initiation. These approaches help to simultaneously reduce soot and NO_x formation. Light-duty diesel engines are well suited for advanced combustion because the higher fuel injection pressures, exhaust gas recirculation (EGR) rates, and boost pressures that aid conventional CI combustion also enable future variations of advanced combustion. In addition, the duty cycle of light-duty diesel engines emphasizes lighter loads where advanced combustion is most easily achieved. Many of the necessary hardware enhancements exist today, although they may be expensive to implement in production engines. Nonetheless, advanced combustion engines are rapidly moving from research into engine development and commercialisation.


Delphi

An early single-cylinder gasoline compression ignition (GCI) test engine developed by Delphi; ongoing development of the GCI concept aims to achieve diesel-like efficiency with low CO_2 emissions under real-world operating conditions.

The gasoline compression ignition concept

From a commercial perspective, it is well understood that there are significant challenges associated with bringing both a new engine concept and a dedicated fuel into the market at the same time. The potential benefits of fuelling advanced CI engines with market gasoline merits further consideration for the following reasons. In general, CI engines have an efficiency advantage over SI engines, and extending their capability to use a broader range of fuels could be advantageous. Second, the ability of CI engine concepts to use an already available market gasoline would allow these concepts to enter the fleet without fuel constraints. Third, more gasoline consumption in passenger cars would help to rebalance Europe's gasoline/diesel fuel demand on refineries and reduce GHG emissions from the fuel supply. Fourth, a successful GCI ('gasoline compression ignition') vehicle could potentially compete in predominantly gasoline markets in other parts of the world.

Because of these potential benefits, it was decided to investigate more completely the GCI engine concept, specifically to determine the range of conditions over which an engine could operate successfully in CI mode on a European market gasoline. In addition to an engineering paper study and a bench engine study on the GCI concept (Rose *et al.*, 2013), computational fluid dynamics (CFD) in-flow and combustion simulations were also carried out (Cracknell *et al.*, 2014).

Computational fluid dynamics is a state of the art simulation tool for analysing the flow behaviour in internal combustion engines. To reduce the computation time, only the combustion chamber and port geometries were modelled in this study.

Two main areas which were modelled were gas exchange and turbulent non-reacting flow which was modelled using STAR-CD®, a CFD programme concentrating on the combustion chamber and the port geometries in conjunction with a 1-D GT-Power simulation which was used to define boundary conditions.

The other area was combustion modelling which was done using KIVA software. The KIVA package included other sub-models for looking at spray, turbulence, wall impingement and other aspects. The STAR-CD® fluid flow was mapped to the KIVA simulations and used as boundary conditions (pressure, temperature, gas composition and flow velocity (see Figure 2).

Engineering paper study

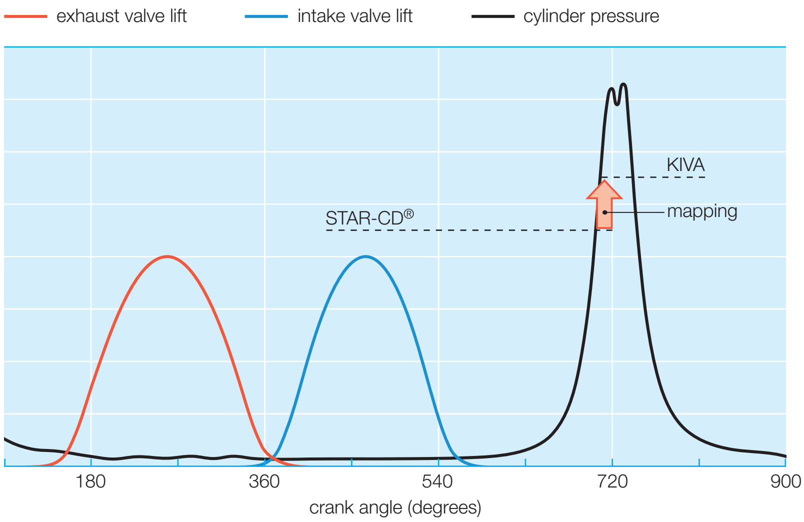
An engineering paper study was first completed to analyse critical engine and fuel parameters and judge what speed/load range might be feasible for a GCI engine concept. For this engineering study, and for the bench engine work that followed, it was assumed that the GCI engine concept would be fuelled with a typical European market gasoline. The only change that was made was the addition of a lubricity additive.

The paper study identified the autoignition resistance of market gasoline as the single most critical challenge, particularly at low load conditions. Three main approaches were identified to mitigate this challenge:

- Shortening the ignition delay by increasing the charge pressure using two-stage boosting and a higher compression ratio (CR).
- The use of internal EGR to increase the local charge temperature in the combustion chamber when needed via a variable valve timing (VVT) strategy. High levels of EGR would be needed to control engine-out NO_x emissions so that both external and internal EGR would be used with a trade-off in local charge temperature between the competing demands of lowering NO_x emissions and achieving stable combustion.
- The use of combustion assistance (e.g. a glow or spark plug) to stabilise combustion at the lowest load points.

The paper study also recognized the important role of fuel spray and mixing, with higher pressure diesel injector systems being preferred along with an optimized combustion chamber geometry.

Figure 2 Computational fluid dynamics (CFD) mapping methodology scheme—STAR-CD® to KIVA



Bench engine study

To test the learnings from the engineering paper study, the bench engine study was carried out to provide a proof of principle for the GCI engine concept, and to determine what hardware measures, including ignition combustion assistance, would be most effective for extending the range of acceptable operation. The results from these tests are presented here, based on the background provided in the 'methodology' section. A more detailed account of the engine results is given in Rose *et al.,* 2013.

The success criteria for the bench engine optimization included the following factors: low engine-out NO_x; PM, HC and CO emissions as low as possible and suitable for further reduction by DOC (diesel oxidation catalyst) and GPF (gasoline particulate filter) aftertreatment systems; engine noise in the same range as conventional diesel CI operation; and fuel efficiency at least as good as the base engine configuration.

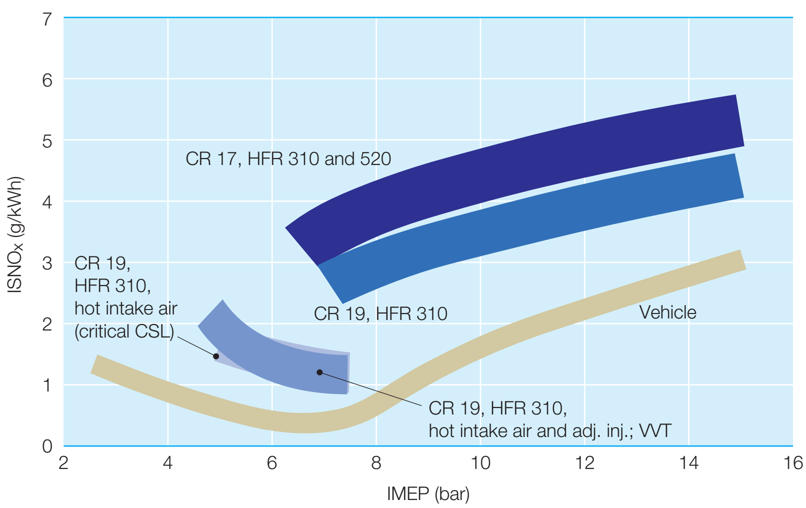
The bench engine included hardware enhancements that enabled it to meet Euro VI emissions limits and beyond. A downsizing concept was employed with a cylinder swept volume of 390 cm^3 that would allow the construction of a 1.6-litre 4-cylinder engine while maintaining the power of today's 2.0-litre engines.

As anticipated by the engineering paper study, it proved difficult to sustain reliable combustion using the market gasoline at lower load operating conditions. Light-load operation could be achieved, but NO_x levels were higher than desired. The combustion was also unstable and would not tolerate additional EGR. For this reason, the engine was fitted with a state-of-the-art glow plug which was capable of a sustained glow temperature of around 1200°C. For these tests, the engine coolant temperature was also reduced to 48°C to simulate the engine warm-up period.

The orientation of the glow plug to the injector spray is known to be critical. The position was adjusted by changing the orientation with respect to one individual injector spray by one-degree increments, while monitoring engine performance. A position close to the spray centre line giving the lowest CO/HC emissions and combustion duration was chosen for testing.

With the glow plug installed, low-load operation was possible at normal boost pressure levels, even at the cooler engine temperature condition. Under hot engine conditions, however, the glow plug did not help to reduce the NO_x emissions. At a 400-bar injection pressure, combustion quality was poor with a higher EGR rate. Reducing the injection pressure further to 260 bars improved combustion, but the increased heat release led to higher NO_x emissions even though the EGR level was already quite high.

Figure 3 Indicated specific NO_x ($ISNO_x$) emissions achievable at 1,500 rpm as a function of indicated mean effective pressure (IMEP)



From the engineering paper study, it was expected that the engine-out NO_x/PM trade-off would be better compared to diesel engines at low engine loads. Figure 3 shows the NO_x levels achieved in this study for the various hardware options tested. The target NO_x levels at 1500 rpm for various loads are shown by the solid band marked 'vehicle'. Even with the optimized injection strategy, higher CR, VVT and hot intake air, the engine was not able to achieve the target NO_x levels without exceeding a reasonable level of HC emissions. With combustion assist in the form of a glow plug, it was possible to achieve loads down to 4.3 bars IMEP as far as the combustion sound limit (CSL) would allow, but not with the EGR levels required to meet the target NO_x levels.

In this study, internal (uncooled) EGR using negative valve overlap was found to be advantageous for reducing HC emissions and improving fuel consumption in the mid-load range.

There are a number of competing effects that occur when more internal EGR is used. For example, higher temperature by itself shortens the ignition delay but also leads to higher NO_x levels which require higher EGR levels to control them. With higher EGR levels, the decrease in local oxygen levels and inhomogeneities associated with the internal EGR concentration led to higher smoke levels and a tendency to lengthen the ignition delay.

Nevertheless, Figure 4 (page 15) shows the brake-specific fuel consumption (BSFC) results, for two different speeds, obtained for the GCI concept compared with the range of state-of-the-art 2012 model-year spark ignition and direct injection compression ignition engines. The GCI concept was found to be well below those of naturally aspirated (NA) and turbo-charged (TC) spark-ignited gasoline engines, and at the bottom end of the range of direct injection diesel engines.

In addition to optimizing the glow plug position and utilising internal EGR to improve gasoline's ignitability under the low load operating conditions, it was concluded that further investigation would be required to find the best configurations of VVT strategy and spray targeting. Thus, three-dimensional CFD simulations were carried out.

Modelling study

Because the engineering study suggested that a glow plug would be required to assist combustion under this low load operating condition, the spray spatial distribution and the local lambda (i.e. air/fuel ratio) were also analysed.

Figure 5 shows the results of the mixture formation analysis performed when the piston is at the top dead centre firing (TDC-F) position for advanced boosted (left) and more realistic boost conditions (right). Here, the spray is visualized inside a 45° mesh sector of the piston bowl, by means of rich lambda iso-volumes coloured by

Figure 4 Brake specific fuel consumption (BSFC) versus engine speed

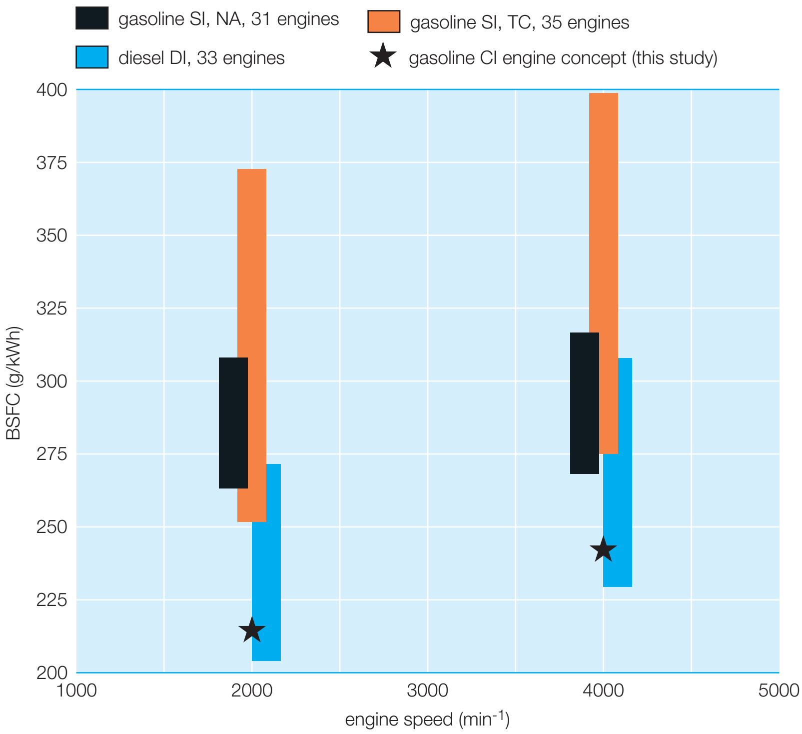
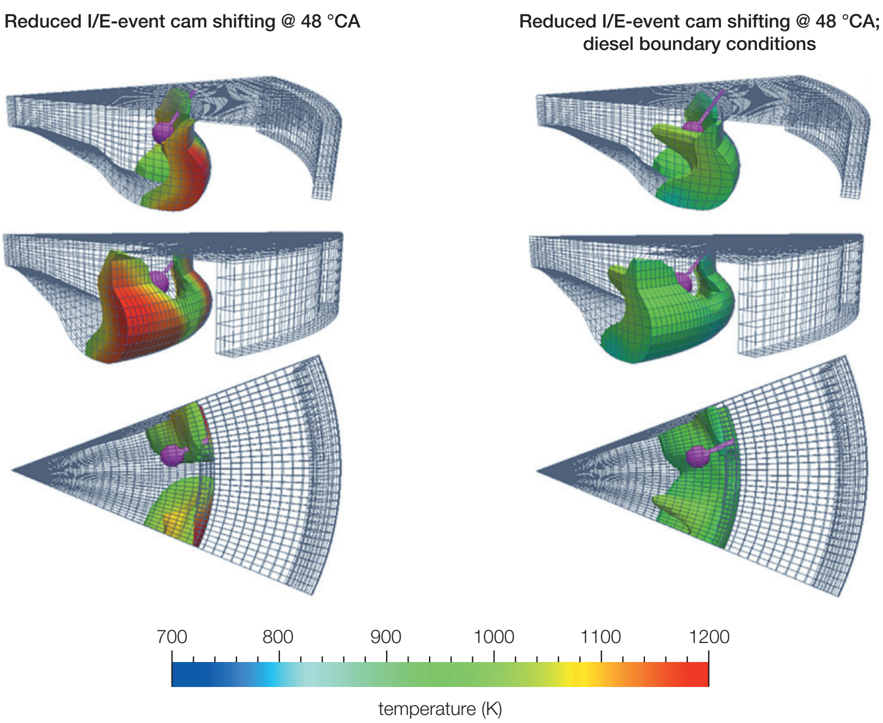


Figure 5 Mixture formation under boosted (left) and more realistic (right) conditions



increasing temperature. Thus, the rich zones, which will probably ignite with the glow plug, are identified. With accurate positioning of the glow plug, a favourable interaction between the fuel spray and glow plug is possible with the chosen nozzle cone angle of 153°. With advanced boosting the glow plug ignites spontaneously. Under more normal boosting conditions the glow plug will need to be heated to ignite the charge.

Further optimization was investigated using simulated spark plug assist instead of a glow plug. Using the optimum nozzle cone angle of 160° and nozzle protrusion of >1.5 mm an ignitable mixture condition around the spark plug is possible.

Apart from the work that Concawe has been doing over a number of years, there is increasing interest in this area of study from others. Delphi is working with Hyundai in collaboration with the University of Wisconsin-Madison's Engine Research Consultants (WERC) and Wayne State University on this topic, with US Department of Energy funding. Argonne National Laboratory and Saudi Aramco are also working on projects in this area of study. With a continuous and increasing trend of gasoline oversupply, an engine that performs at diesel engine fuel efficiency but running on gasoline components seems to be a practical and effective way forward to reduce costs and well-to-wheels (WTW) emissions.

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