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Diesel vehicles and sustainable mobility in the U.S.

T.J. Wallington*, C.K. Lambert, W.C. Ruona

Research and Advanced Engineering, Ford Motor Company, Dearborn, MI 48121-2053, USA

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ABSTRACT

Concerns regarding global warming and energy security have increased the importance of decreasing emissions of CO_2 from vehicles. Diesel vehicles have higher fuel economy and lower CO_2 emissions than their gasoline counterparts. On a well-to-wheels per vehicle per km basis it has been estimated that diesel light-duty vehicles in 2015 will emit 14–27% less CO_2 than their gasoline counterparts. We estimate here that on a gCO_2/kWh *at peak torque*, diesel medium-duty vehicles currently have an approximately 10% CO_2 advantage over their gasoline counterparts. At light and moderate loads the CO_2 advantage for medium-duty diesels with SCR after-treatment will be greater than 10% (reflecting pumping losses when gasoline engines are operated at low and moderate loads). Emission of NO_x, HCs, and PM from diesel (and gasoline) vehicles has decreased substantially over the past decade and further reductions are anticipated in the future. In addition to the heavy-duty segment, which diesels currently dominate, modern diesel engines are likely to continue to play an important role in the medium-duty segment, and perhaps also in the light-duty segment in a transition to more sustainable mobility.

1. Introduction

Climate change and energy security are long-term challenges facing society. The U.S. is fortunate in having large reserves of coal (approximately 250 years of supply at the current rate of production (British Petroleum, 2010)) and natural gas (technically recoverable resources including shale gas deposits are equivalent to approximately 100 years of supply at the current rate of production (USEIA, 2011)). However, U.S. reserves of petroleum are limited, domestic production is in a long term decline and has fallen from a peak of 11.3 million barrels per day in 1970 to 7.2 million barrels per day in 2009 (British Petroleum, 2010). Over the same period the consumption of oil in the U.S. has increased from 14.7 to 18.7 million barrels per day (British Petroleum, 2010) and the fraction of oil demand that is met by imported oil increased from approximately 20% to 60%. Approximately 94% of U.S. transportation energy demand is supplied by petroleum (USEIA, 2009). This nearly complete dependence of a vital economic sector on a dwindling domestic energy resource is clearly a source of concern.

Climate change is caused by increasing levels of greenhouse gases in the Earth's atmosphere resulting from human activities (IPCC, 2007). CO_2 released during fossil fuel combustion and deforestation is the largest contributor to radiative forcing of climate change (IPCC, 2007). Road transportation in the U.S. and EU-15 is responsible for approximately 5% and 4% of global fossil fuel CO_2 emissions, respectively (Wallington et al., 2008). On a global basis, in 2007 road transportation was responsible for approximately 5 Gt of global fossil fuel CO_2 emissions (WBCSD, 2004), which represents about 17% of the approximately 30 Gt total global emissions. The United Nations Framework Convention on Climate Change has been ratified by 192 countries and calls for stabilization of greenhouse gas concentrations in the atmosphere at a level that would "prevent dangerous anthropogenic interference with the climate system" (UNFCCC, 2008). While there is no consensus on a precise level of CO_2 in the atmosphere that would prevent such interference, levels in the range 450–550 ppm have been discussed. Meeting these targets will require the research, development, and deployment of new low-CO_2 vehicle technologies.

The development of mobility solutions that are economically, environmentally, and socially sustainable is a major challenge. Fortunately, there are several vehicle technologies that are supportive of a sustainable future. In the present paper we focus on the opportunities and challenges of advanced diesel engines from a U.S. perspective.

Higher fuel costs and the regulatory landscape in Europe favor diesel light-duty vehicles (LDVs) more than in the U.S. and consequently the market penetration of diesel LDVs is higher in Europe than in the U.S. Medium- and heavy-duty vehicles consume larger amounts of fuel than LDVs and hence diesel powertrains are more attractive in these applications. We have previously reported an assessment of diesel light-duty vehicles in which we concluded that on a well-to-wheels per vehicle per

* Corresponding author. Tel.: +1 313 390 5574.
E-mail address: twalling@ford.com (T.J. Wallington).

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km basis, diesel LDVs in 2015 will emit 14–27% less CO_2 than their gasoline counterparts (Sullivan et al., 2004). In the present paper we concentrate on class 2b (8501–10,000 lbs gross vehicle weight rating [GVWR]), and class 3 (10,001–14,000 GVWR) medium-duty trucks (reflecting their importance in the U.S. market). We provide an overview of biofuels for diesels, medium-duty diesel emission regulations, advanced diesel technology, progress in reducing the emissions of criteria pollutants, and the CO_2 benefit of medium-duty diesel vehicles from a U.S. perspective.

2. Diesel vehicles in perspective

Diesel and gasoline engines have fundamentally different modes of operation. In diesel engines, the fuel autoignites as it is sprayed into the combustion chamber. A spark is not required to ignite the diesel fuel, which is a heavier, less volatile mixture of hydrocarbons than gasoline and chemically more susceptible to autoignition. Relative to gasoline engines, diesel engines have higher compression ratios, more rapid combustion, lower throttling losses, and operate leaner (i.e., at a greater air–fuel ratio). As a result, diesel engines have an inherently greater thermodynamic efficiency than gasoline engines. Diesel fuel also has approximately 12% greater volumetric energy content than gasoline; hence diesel engines operate with a higher volumetric fuel economy (lower fuel consumption) than gasoline engines.

With higher fuel efficiency, superior torque, and greater durability, it is not surprising that diesel vehicles dominate the heavy-duty truck market. At the other end of the vehicle size spectrum the diesel market share for passenger cars in the U.S. over the past 20 years has typically been less than 1%. The U.S. Department of Transportation classifies trucks by the gross (i.e., loaded with freight and passengers) vehicle weight as follows: Class 1 are 0–6000 lbs (e.g., Ford Ranger, Toyota Tacoma); Class 2 are 6001–10,000 lbs (e.g., Ford F-150); and Class 3 are 10,001–14,000 lbs (e.g., Ford Super Duty). Class 2 is subdivided into Class 2a (6000–8500 lbs) and Class 2b (8501–10,000 lbs). Fig. 1 shows the diesel market share in the U.S. for new vehicles of these different size classes. Data were taken from Davis et al., 2010 and the RL Polk Database. As seen from Fig. 1, there is a significant trend of increased diesel share with increased weight of the vehicle and the trend over the past 20 years suggests that the popularity of diesel light-duty vehicles is increasing (albeit from a very low base). Challenges facing the more widespread adoption of light-duty diesels in the U.S. include the recent change in the price differential between diesel and gasoline (see Fig. 2), significantly higher cost of diesel engine and aftertreatment technology, and the lower density of diesel fueling stations.

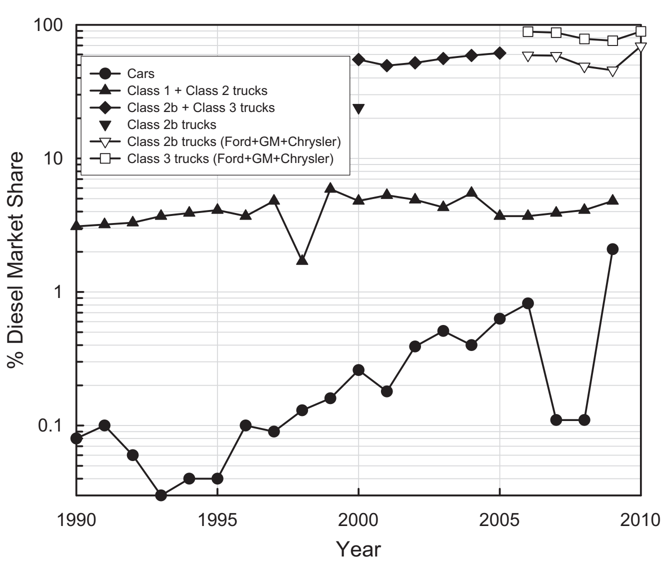

Fig. 1. Diesel fraction of new vehicle sales in the U.S. of cars (circles), Class 1+Class 2 trucks (triangles), Class 2b trucks (inverted triangle), and Class 2b+Class 3 trucks (diamonds).

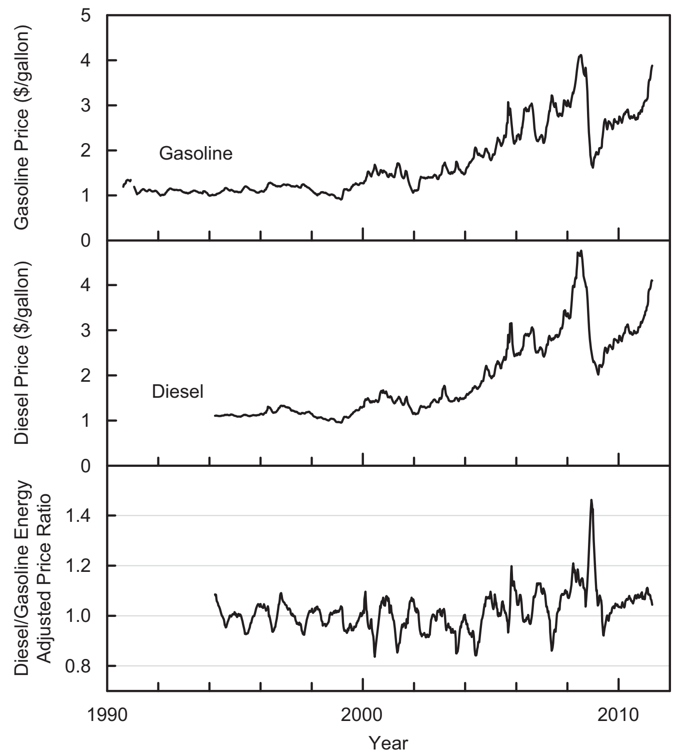

Fig. 2. U.S. fuel prices (Energy Information Agency, 2011).

3. Biomass-derived diesel fuels: biodiesel, renewable diesel, green diesel, and BTL

There has been a substantial increase in the U.S. production of biofuels over the past decade. There are several routes to convert biomass into fuel suitable for diesel engines and the nomenclature can be confusing. Currently fatty acid methyl esters (FAMEs) made from transesterification of plant oils or animal fats make up the vast majority of biomass-derived diesel fuel both in the U.S. and globally. FAME is typically blended into petroleum diesel before use (e.g. at 2% [B2] to 20% concentration [B20]). FAME is usually referred to as "biodiesel", which is distinct from hydrotreated (and sometimes isomerized) vegetable oils or animal fats, which are referred to as "renewable diesel" or "green diesel". There is research and development directed at improving the thermochemical conversion of biomass-to-liquid (BTL) fuels. One BTL option is gasification of biomass to give synthesis gas (mixture of CO and H_2), which can be passed over a catalyst and converted into alkanes via the Fischer–Tropsch synthesis. The Fischer–Tropsch synthesis produces a mixture of normal (straight-chain) alkanes; it is well suited to the production of diesel fuel, but it can also be used to produce shorter alkanes, which can be blended into gasoline. Another BTL option is the pyrolysis of biomass to produce bio-oil, which can be blended with conventional oil and processed in a refinery. Renewable diesel and BTL are hydrocarbons and fully fungible with fossil diesel. Biodiesel is not fully fungible with fossil diesel. Care needs to be taken to ensure adequate oxidative stability and cold flow