

An Efficient, Durable Vocational Truck Gasoline Engine

Thomas Reinhart and Marc Megel
Southwest Research Institute

ABSTRACT

This paper describes the potential for the use of Dedicated EGR® (D-EGR®) in a gasoline powered medium truck engine. The project goal was to determine if it is possible to match the thermal efficiency of a medium-duty diesel engine in Class 4 to Class 7 truck operations. The project evaluated a range of parameters for a D-EGR engine, including displacement, operating speed range, boosting systems, and BMEP levels. The engine simulation was done in GT-POWER, guided by experimental experience with smaller size D-EGR engines.

The resulting engine fuel consumption maps were applied to two vehicle models, which ran over a range of 8 duty cycles at 3 payloads. This allowed a thorough evaluation of how D-EGR and conventional gasoline engines compare in fuel consumption and thermal efficiency to a diesel. The project results show that D-EGR gasoline engines can compete with medium duty diesel engines in terms of both thermal efficiency and GHG emissions. Since gasoline has less energy per gallon than diesel, the D-EGR engine will have higher fuel consumption in gallons than the diesel, but the higher price of diesel fuel makes up for this difference in the US market.

D-EGR also results in much lower in-cylinder and exhaust temperatures, which will help improve durability compared to a conventional gasoline engine. A D-EGR engine with its 3-way catalyst will be far cheaper than a diesel with DPF and SCR, so there is an opportunity for gasoline engines to regain medium truck market share.

CITATION: Reinhart, T. and Megel, M., "An Efficient, Durable Vocational Truck Gasoline Engine," *SAE Int. J. Engines* 9(3):2016, doi:10.4271/2016-01-0660.

INTRODUCTION

In a project for NHTSA, SwRI evaluated a range of potential fuel saving technologies for trucks ranging from Class 2b (3/4 ton pickups) to long haul tractor-trailer trucks [1, 2, 3, 4, 5]. Part of this project involved looking at both gasoline and diesel engine fuel saving technologies. One striking outcome was the efficiency potential for downsized and boosted gasoline engines using EGR. EGR allows gasoline engines to avoid or limit the timing retard that is normally required to avoid knock at low speed and high load. EGR also allows the engine to avoid the enrichment that is normally used to limit temperatures at high speed and load. A third benefit of EGR is reduced pumping work at light load. As a result, downsizing and boosting with the use of EGR leads to substantial improvements in gasoline engine brake thermal efficiency.

The results of the NHTSA project suggest that for a medium truck application, it should be possible to approximately match the thermal efficiency of a modern diesel engine using a boosted gasoline engine using D-EGR. The purpose the project described in this paper was to explore the range of displacements, BMEP, and speed ranges that could be used, and determine the best parameter combinations for a gasoline D-EGR medium truck engine. SwRI has been working on D-EGR engines for several years. The work has been conducted

using internal research funding, projects conducted by the HEDGE consortium (High Efficiency Dilute Gasoline Engine), and single client projects. A recent light duty passenger car D-EGR project is documented in [6].

HISTORICAL BACKGROUND

In the 1940s and 1950s, most medium- and heavy-duty trucks in North America were powered by gasoline engines. The same was true of off road equipment such as agricultural tractors and construction equipment. In the 1960s and 1970s, diesel engines took over the market for heavy duty trucks, and in the 1980s diesel engines went from a small share of vocational trucks to the dominant share. The factors driving the diesel takeover of the truck market were fuel economy, performance, and durability. These factors were enough to overcome the cost penalty of the relatively simple, mechanically controlled diesel engines of the time.

Traditionally, a gasoline engine in a medium duty truck suffers from a 25% to 35% fuel consumption penalty compared to a diesel, on a volume (gallon) basis. About 13% to 16% of this penalty reflects the difference in energy content between E10 gasoline and diesel fuel.

but 9% to 22% of the higher fuel consumption is due to lower thermal efficiency of the gasoline engine. There are three large sources of this thermal efficiency penalty:

- The gasoline engine must run rich at high speed and load in order to limit engine and catalyst temperatures
- The gasoline engine must use a lower compression ratio to avoid knock
- The gasoline engine suffers high pumping losses at light load due to throttling

In this paper, fuel consumption, energy consumption and thermal efficiency will be used to compare engines, rather than the traditional fuel economy values. As a result, some discussion of these parameters is in order. Fuel economy is typically measured in units of miles driven per gallon consumed (MPG). Fuel consumption of a vehicle can be expressed in units of gallons consumed per 100 miles driven, or in liters per 100 km. For an engine, fuel consumption is most often expressed in units of grams of fuel per kilowatt-hour, but it can also be in terms like gallons per 100 HP-hours. Fuel consumption is a linear effect, while fuel economy is non-linear. For example, if fuel consumption is reduced by 50%, it will take half the number of gallons of fuel to complete a given trip, and fuel cost also goes down by 50%. In that same circumstance, however, fuel economy is increased by 100%. A 100% increase in fuel economy does not mean that you save 100% of the fuel cost.

Energy consumption and thermal efficiency are related. If two engines have the same thermal efficiency, they will consume the same amount of energy to do a given amount of work. Energy consumption and/or thermal efficiency are important terms to use when comparing engines that use different fuels, such as gasoline, diesel fuel, and natural gas. If two engines have the same energy consumption and thermal efficiency, but the two fuels have different energy content per gallon, the two engines will have different fuel consumption (in volume units) to accomplish the same task. Energy consumption or thermal efficiency are the correct terms to use in comparing the efficiency of two engines using different fuels, but the vehicle operator buys gallons or liters of fuel, so fuel consumption by unit volume is also important.

Another issue to consider when changing fuels is CO₂ emissions. Gasoline has a slightly higher hydrogen to carbon ratio than diesel, so CO₂ emissions with gasoline will be about 1% less in a situation where both engines have the same thermal efficiency. There is considerable dispute about how to handle the carbon content of ethanol in E10 gasoline, but blending with ethanol can give gasoline an additional CO₂ advantage over diesel.

The durability of heavy duty gasoline engines, compared to diesels, suffers from two main factors. The first is that gasoline engines normally run stoichiometric, while diesel engines run lean. The lean operation of diesel engines results in much lower combustion chamber and exhaust temperatures for the diesel. The high temperatures of stoichiometric gasoline engines result in a significant durability penalty. The second factor affecting gasoline engine

durability is that many heavy duty gasoline engines are derivatives of light duty engines, so they do not always include features required to achieve good durability under demanding operating conditions.

Naturally aspirated gasoline engines suffer a performance penalty compared with turbocharged diesel engines. The strong low speed torque of turbocharged diesels is a very desirable characteristic in a medium or heavy truck.

Recent technical developments for gasoline engines, such as the introduction of direct injection, turbocharging, and cooled EGR, have the potential to greatly reduce or eliminate all three main sources of the fuel consumption penalty of gasoline engines. EGR dilutes the charge in the cylinder, which reduces both in-cylinder and exhaust system temperatures. The lower temperatures from EGR improve durability, as can be seen in modern heavy-duty natural gas engines, which utilize cooled EGR to control temperatures under stoichiometric operation. Turbocharging of gasoline engines also allows the creation of torque curves that offer performance similar to what is available with diesel engines.

As an example of the effect of cooled EGR on fuel consumption, Figure 1 shows the fuel consumption penalty of two engines with EGR, compared to a baseline 6.7 liter diesel. One engine is a 3.5 liter V-6 boosted gasoline engine with cooled high pressure loop EGR (not D-EGR) and VVA (labeled P16), and the second alternative is a 6.2 liter naturally aspirated V-8 engine equipped with GDI, EGR, cylinder cutout, and a 10% reduction in FMEP (P20). Figure 1 also shows the fuel consumption of a conventional 6.2 liter port-injected, naturally aspirated gasoline V-8. Figure 2 is a photo of the Kenworth T270 truck that was used in these simulations.

The results shown in Figure 1 were obtained by putting fuel maps for all three engines into a vehicle simulation model. The fuel maps were created in GT-POWER, with extensive engine test cell data used both to supply model inputs and for engine model validation. The vehicle's final drive ratio was modified to fit the speed characteristics of each engine. All engines had adequate performance (approximately 300 HP) to follow the drive cycles and achieve similar 0 to 60 MPH times. The results shown in Figure 1 come from a study conducted by SwRI for NHTSA [1].

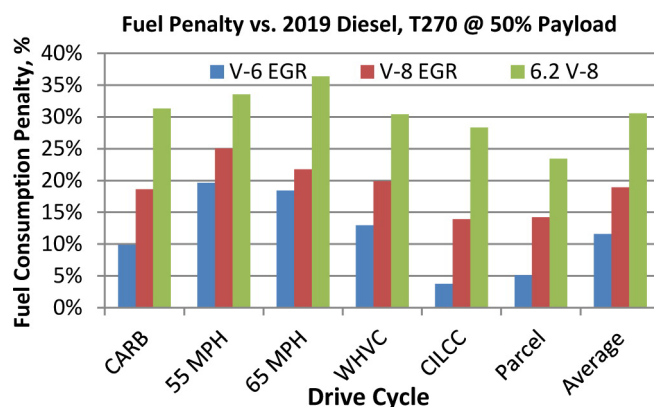


Figure 1. Fuel consumption penalty of 3 engine alternatives compared to a 2019 diesel baseline: a baseline 6.2 liter gasoline V-8, a naturally aspirated V-8 and VVA, including naturally aspirated V-8 and turbo V-6 gasoline engines.



Figure 2. Kenworth T270 truck used in simulations of gasoline engines with cooled EGR, compared to a projected 2019 diesel.

Averaged over six drive cycles, the downsized, boosted gasoline engine just exceeds the thermal efficiency of the diesel, with a fuel consumption penalty of 12% compared to a simulated 2019 diesel. In general, the gasoline engine performed best in drive cycles with low average power demand, where the larger displacement diesel is working at low (and thus inefficient) BMEP levels. The NHTSA study did not consider the possibility of using dedicated EGR (D-EGR). With D-EGR, the engine should be somewhat more efficient than the engines simulated for NHTSA.

One factor contributing to the good fuel consumption of the 3.5 liter V-6 engine shown in Figure 1 is the fact that this engine is derived from a passenger car engine. This means that the engine has low friction (FMEP); it is lower than can be expected of a more heavy duty engine. Applying more realistic FMEP values would increase the fuel consumption of this engine. The effects of FMEP will be discussed in more detail below.

The Fuel Price Factor

Historically, up until October 2005, diesel fuel averaged slightly cheaper than gasoline in the USA, although the Federal tax on diesel fuel is 6 cents per gallon higher for diesel. A lower pump price for diesel makes sense, since the refining cost of diesel fuel is lower than that for gasoline. However, from 2005 through 2014, diesel fuel has averaged 28 cents per gallon higher than gasoline. In 2014, diesel averaged 47 cents per gallon higher, and at the end of December, the difference was 82 cents per gallon. So far this year, diesel is averaging 52 cents higher than gasoline (see Figures 3 and 4).

The price differential between gasoline and diesel fuel has fluctuated widely over the last 9 years. In the last few years, a predictable seasonal pattern has emerged in the US market (Figure 5). In winter, when demand for home heating oil peaks and gasoline demand is lower, the diesel price premium is large. In summer, when there is little demand for heating oil and gasoline demand is higher, the diesel price premium is much smaller or even negative. The price premium for diesel is driven by the world fuel market, where demand for diesel tends to be ahead of supply, while demand

for gasoline tends to run behind the supply. Projections of future demand indicate that diesel demand will continue to grow, as gasoline demand levels off [9]. This effect is expected to increase the price pressure on diesel. As a result of the diesel fuel price premium, a diesel engine must be significantly more efficient in gallon terms, just to make up for the higher fuel cost in the US market. The fuel price situation in other countries varies considerably, due to differences in the fuel tax structure in different markets.

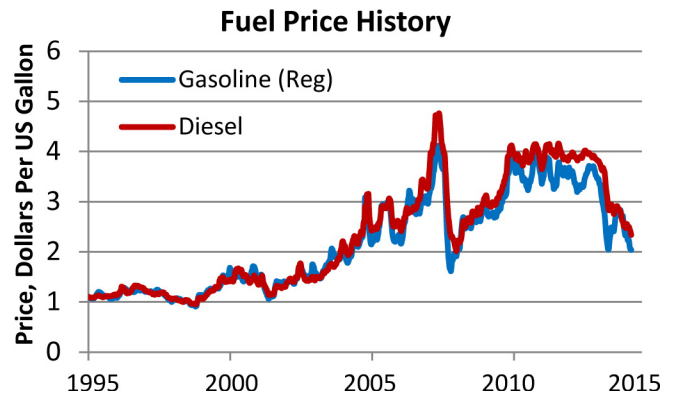


Figure 3. Price history of regular gasoline and diesel fuel in the US market.

The only high volume medium-duty truck that is currently offered in the US market with a gasoline engine option is the Ford F-650 / 750. The engine offered in these trucks is a conventional port-injected, naturally aspirated 6.8 liter V-10 which was derived from a pickup truck engine. From the Ford web site, in January 2015 the price difference between the V-10 gasoline engine and the Cummins ISB diesel is \$10,965 [7]. This price difference is driven by the more expensive diesel engine and HPCR fuel system, but mostly by the DPF + SCR aftertreatment required by a diesel. The gasoline engine gets by with a simple 3-way catalyst. The combination of high diesel engine and aftertreatment prices, the high diesel fuel price relative to gasoline, and new high efficiency gasoline engine technology opens an opportunity for a cost-effective, fuel efficient gasoline medium truck engine.

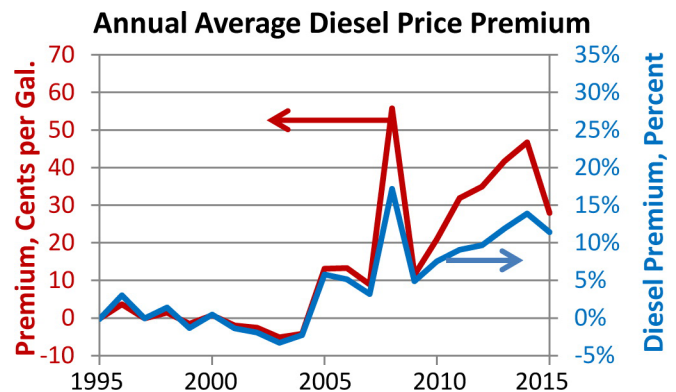


Figure 4. History of Diesel fuel price premium per gallon over regular gasoline in the US market. Data through December 14, 2015.

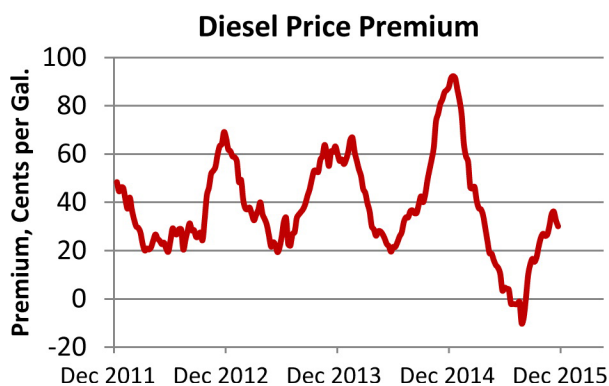


Figure 5. Diesel fuel price premium, December 2011 through 2015.

The objectives of the project described here were:

- Develop a GT-Power model to simulate a heavy duty gasoline engine
- Exercise the model to explore factors that can affect efficiency
 - Displacement vs. boosting technology trade-offs (single stage, larger engine vs. two stage, smaller engine)
 - Displacement vs. operating speed range trade-offs (small, high speed engine vs. larger, lower speed engines)
 - Vehicle fuel consumption with D-EGR vs. diesel over a range of vehicle size, payloads, and drive cycles
- Demonstrate via simulation that a D-EGR gasoline engine can provide competitive fuel consumption in medium duty trucks

The following key questions were to be resolved:

1. Is there a fuel consumption advantage in a small displacement, high speed engine compared to a larger displacement, lower speed engine?
2. Is there a fuel consumption advantage in a high BMEP engine with two stage boost, compared to a lower BMEP (and thus higher displacement) engine with single stage boost?

EVALUATION OF D-EGR ENGINE OPTIONS

Several GT-POWER engine models were developed and evaluated to explore the range of possible design parameters for a D-EGR medium-duty truck engine. At the beginning of the project, the project team agreed that the basic engine layout should be an inline 6-cylinder engine, which is the standard configuration for medium-duty diesel engines. Since higher EGR rates allow better engine efficiency, the highest practical rate was used for this study. 33% EGR is near the upper limit that can be used while still obtaining reliable combustion, which means that on a six cylinder engine there are two rich running D-EGR cylinders and four conventional stoichiometric cylinders. At light load, misfire becomes a potential problem with 33% EGR, so at 2 bar BMEP and below, 17% EGR

(one D-EGR cylinder) was used. The GT-POWER models were then used to explore a range of BMEP, engine speed range, and engine displacement.

As a program target, the Cummins ISB diesel with a rating of 300 HP @ 2,600 RPM and 660 lb-ft at 1,600 RPM was selected. This is the top rating for the automatic transmissions that are widely used in medium-duty trucks. The fuel map for an anticipated 2019 version of the ISB from the NHTSA engine and vehicle efficiency project was used in this research. This projected 2019 fuel map will provide fuel consumption 3% to 4% lower than that of a 2012 ISB engine that has been tested at SwRI. Since any new gasoline engine must compete with future diesel engines, this choice of engine baseline is appropriate. The proposed gasoline engine torque curves were intended to allow identical vehicle performance compared to the diesel. Since the gasoline engines would use a higher speed range, the vehicle axle ratio was modified to maintain vehicle performance. In other words, if the engine rated speed is increased from 2,600 RPM to 3,500 RPM, the axle ratio will be increased by a factor of 3,500/2,600 to maintain the same power at the wheels for both engines.

Gasoline engines typically have a much higher maximum speed than diesels. For light duty applications, maximum speeds of 5,000 to 7,000 RPM are common. For a medium duty application, a lower speed range is likely to be desirable, due to a need to reduce both wear and fuel consumption. In this study, a range of rated speeds from 3,500 RPM to 5,000 RPM was considered. This led to the development of a family of potential torque curves, which are shown in Figures 6 through 8. Each figure shows the same family of torque curves, but the data is presented in different formats to help the reader see what is going on. Figure 6 shows the conventional speed vs. torque plot that most readers will be familiar with. Figure 7 shows the same torque curves, but in a percent speed vs. torque display, where 100% speed is the highest speed at which full power is produced. This figure shows that the torque curves have identical characteristics in terms of percent of maximum torque versus percent of maximum speed. Figure 8 shows power vs. percent speed. This shows that the power curves are identical except down near idle RPM.

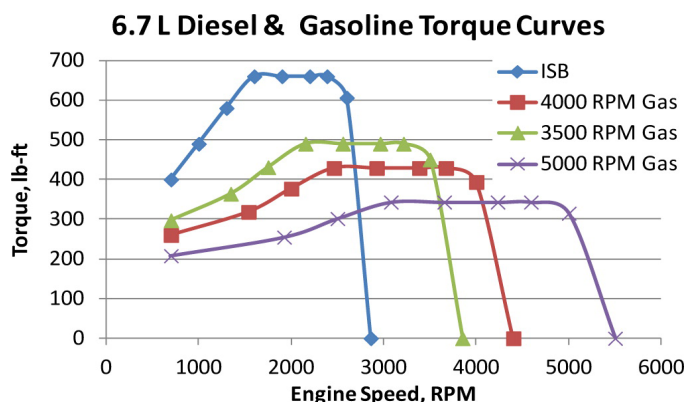


Figure 6. Torque vs. speed for a range of gasoline engine rating options.