Topic Paper #4

Alcohol Boosted Turbo Gasoline Engines

On August 1, 2012, The National Petroleum Council (NPC) in approving its report, *Advancing Technology for America's Transportation Future*, also approved the making available of certain materials used in the study process, including detailed, specific subject matter papers prepared or used by the study's Task Groups and/or Subgroups. These Topic Papers were working documents that were part of the analyses that led to development of the summary results presented in the report's Executive Summary and Chapters.

These Topic Papers represent the views and conclusions of the authors. The National Petroleum Council has not endorsed or approved the statements and conclusions contained in these documents, but approved the publication of these materials as part of the study process.

The NPC believes that these papers will be of interest to the readers of the report and will help them better understand the results. These materials are being made available in the interest of transparency.

White Paper For National Petroleum Council Study

Alcohol Boosted Turbo Gasoline Engines

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Technology

Low incremental cost is needed to obtain large volume utilization of clean, high efficiency engines for light-duty vehicles. The alcohol boosted turbo gasoline engine concept addresses this need by high pressure turbocharged gasoline engine operation that provides efficiency comparable to a diesel engine* at substantially lower cost along with lower vehicle air pollutant emissions and increased power (1, 2, 3,4). High-pressure operation is enabled by optimized use of a small amount of alcohol which removes the gasoline engine's knock constraint at high torque. Alcohol boosted turbo gasoline engines can also be employed in heavy-duty vehicles.

In order to provide diesel-like efficiency, the alcohol boosted turbo gasoline engine uses a high-pressure engine block that has strength approaching that of a diesel block. The engine is operated with a high compression ratio (12-15), a high manifold pressure (2. 3 - 2.5 bar at wide open throttle) and a stoichiometric fuel/air ratio (in contrast to the lean operation employed in a diesel engine). It provides a substantial cost savings relative to a diesel engine by use of a less expensive, much simpler, and more effective exhaust emission control system. Stoichiometric operation with a three-way catalyst is employed in contrast to the particulate filter and nitrogen oxide control systems needed in diesel engines to meet U.S. emissions regulations. The cost is also reduced by use of lower pressure fuel injectors than diesel engines

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* The term fuel efficiency refers to the fuel economy of the powertrain being discussed in a typical vehicle in normal on-road driving. Throughout this paper, it is expressed as an average "efficiency," or in miles per unit energy (or gasoline equivalent) consumed. This avoids the complexity of the roughly 10% higher energy content of a gallon of diesel relative to a gallon of gasoline.

and by a smaller size engine for the same maximum torque. The use of the three-way catalyst provides greater robustness for meeting the possibility of more stringent emissions regulations in the future. Higher power capability is available because of the ability for engine operation at substantially higher engine speed.

As shown in figure 1, alcohol from a secondary tank is directly injected into the cylinders when needed to prevent knock that would otherwise occur at high torque with gasoline. The secondary tank could be completely separate from the primary fuel tank or the primary and secondary tanks could be separate compartments in one fuel tank. The vaporization cooling from the directly -injected alcohol provides a large increase in knock resistance. The knock resistance from ethanol's evaporative cooling impact is equivalent to about 20 octane numbers (5). The alcohol can be in the form a fuel delivered from a pump (*e.g.* E85 or another high ethanol concentration mixture with gasoline in the US and Brazil, or a methanol blend in China). Alternatively it can be an alcohol–water mixture provided in containers. The alcohol–water mixture could be similar to windshield washer fluid without the detergent (or windshield washer fluid itself might be used) and could be distributed using this widespread well-established distribution system. The amount of fluid needed to provide a certain level of knock resistance is reduced by around a factor of two if an alcohol–water mixture or methanol is used instead of E85.

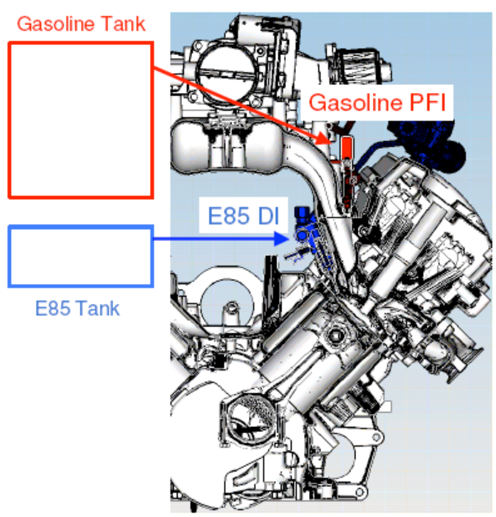

Figure 1. Cross section illustrating engine where E85 is directly injected and gasoline is port fuel injected (6)

A control system is used to minimize the alcohol consumption, by using it only in the amount needed to prevent knock. The control system also maintains a stoichiometric fuel/air ratio as the alcohol/gasoline ratio is changed. The alcohol amount required increases as torque increases. Below a certain normalized torque or BMEP (brake mean effective pressure) level no alcohol is needed (for example, below two-thirds of the maximum torque). Above this torque the alcohol/(gasoline + alcohol) ratio increases with increasing torque. Active feedback control is employed with a knock sensor. Additional control using a lookup table can also be employed. The strong knock suppression provided by direct alcohol injection in combination with an optimized control system enables knock-free engine operation at very high pressure with minimum alcohol consumption. Since operation at high torque in light- duty vehicle driving is infrequent, the total amount of alcohol that is needed in normal driving is small relative to the gasoline that is consumed.

Regular gasoline is used and can be either port injected or directly injected. For typical light-duty vehicle driving, direct injection of the gasoline, due to its cooling effect, has the advantage of reducing the alcohol fluid consumption by a factor of three relative to port fuel injection (2), (3). Direct injection of gasoline can be implemented by use of a single injector which can be fueled with both gasoline and alcohol and has capability for rapid change of the alcohol/gasoline ratio (this technology requires a modest development effort). Alternatively the use of direct injection of gasoline could be implemented by use of a single injector with two valves or by two direct injectors (which may be suitable for larger cylinders where there is sufficient space).

In a vehicle driven in a typical light duty driving cycle such as the Ford Metro–Highway or FTP cycle, where there is little operation at higher relative torque levels, the alcohol use in an alcohol boosted engine with efficiency comparable to diesel efficiency can be limited to a very small fraction of gasoline use (*e.g.* 1 - 2%). This use of an extra fluid is similar to that of urea for urea-SCR diesel exhaust aftertreatment. The alcohol consumption is lower for vehicles with lower compression ratios and/or lower levels of turbocharging.

When the fuel efficiency loss in a light- duty diesel engine with a low-emission exhaust system is taken into account, the overall energy efficiency of an alcohol boosted engine can be comparable to that of a diesel engine and as would the CO_2 emissions .The use of a diesel particulate filter (DPF) results in ~ 2 - 4% loss in efficiency. When a 1 - 2% energy consumption penalty from the production of the urea for urea-based SCR NO_x exhaust treatment is taken into account, the overall efficiency loss is 3 - 6%. The urea-SCR exhaust system loss is less significant in a heavy-duty vehicle. For smaller diesel engines in light–duty vehicles that use a lean NO_x trap instead of urea SCR, the efficiency penalty associated with the NO_x control is ~ 5% due to the use of fuel rich mixture for the trap regeneration. In combination with the DPF efficiency penalty this results in a total efficiency penalty of some 7 - 9%.

Thus an alcohol boosted gasoline engine with a high- pressure block can provide an efficiency gain of some 15% relative to a GTDI (gasoline turbocharged direct injection) engine with the same maximum torque for typical light -duty driving. Around half of this efficiency improvement is due to higher compression ratio and the other half is due to the downsizing and engine downspeeding enabled by the higher level of turbocharging.

An alcohol boosted gasoline engine can provide a range of combinations of improved efficiency and performance relative to a GTDI engine. On the other end of the spectrum to the 15% efficiency gain with the same maximum torque in a downsized engine, an alcohol boosted gasoline engine could provide at least a factor of two increase in the maximum knock–free torque in an engine of the same displacement.. At engine displacements in between, it could provide around a both a significant increase in efficiency as well as in maximum torque.

A different configuration of the alcohol boosted turbo gasoline engine concept is to employ simpler and lower cost port fuel injection for both the alcohol and the gasoline. Relative to direct injection, the use of port injection of alcohol reduces the fuel vaporization cooling effect since vaporization occurs largely in the intake port drawing heat from the walls, thereby decreasing the maximum knock-free compression ratio/turbocharging benefit, and increasing the alcohol requirement averaged over a drive cycle. However, this configuration can be of value for applications where the maximum efficiency gain is traded off for lower cost and simplicity and/or where ethanol or methanol is readily available from a public pump or a central fleet fueling facility

One option for a port- injected alcohol boosted engine is to operate at the same boost pressure as a GTDI engine but with higher compression ratio. This provides an 8-10% efficiency above a GTDI engine if the compression ratio is increased to the 13 -14 range. If a conventional rather than high pressure engine block can be used the cost could be similar to the GTDI engine with the lower cost of the port-fuel-injection system compensating for the cost of the additional tank for the alcohol and control system.

Alcohol boosted gasoline engines could be used in heavy-duty vehicles that operate much of the time at lower loads (urban trucks, buses) and in vehicles that have prolonged operation at high torque. Long haul trucks would require substantially higher average alcohol consumption (*e.g.* E85 consumption equal to around 25% of gasoline consumption) because of their prolonged operation at high torque.

The alcohol boosted gasoline engine concept can also be utilized in flex-fuel engines for both light and heavy-duty vehicles where various mixtures of ethanol or methanol (*e.g.* E85 and/or M85) with gasoline can be used in the primary fuel tank. The fuel tank system can be designed so that the secondary tank is automatically topped off every time the primary tank is filled with ethanol or methanol. For typical light-duty driving where alcohol is used as a primary fuel automatic refill of the secondary tank every few months could reduce or eliminate the need for a special refill of the secondary tank. This option would allow an FFV engine to operate at higher compression ratio and thus more efficiently than today’s FFV engines (whose efficiency and performance is limited by the knock limit when operating in gasoline).

A further application of alcohol boosting is use with CNG and CNG-gasoline engines. Alcohol boosting would both enhance the octane rating of the natural gas and compensate for variations in octane number. It can enable diesel-like efficiency from these engines and increase performance in CNG operation.

Players and State Of Maturity

The direct injection alcohol boost turbo boost spark–ignition engine concept was originated at MIT (1,2,3,4). Commercialization was then pursued by Ethanol Boosting Systems, LLC (EBS), which was spun off from MIT. Extensive MIT and EBS computer modeling of the effect of alcohol injection on knock suppression and effective octane number and engine experiments have been carried out. Figure 2 shows computational modeling results for the relationship between intake manifold pressure and ethanol to gasoline plus ethanol fuel ratio (the "ethanol energy fraction") for knock free operation for two different compression ratios and for both port and direct injection of gasoline (at low engine speeds). Spark retard was not included in these studies. As discussed later on, with moderate spark retard with its modest torque reduction substantially reduces the ethanol energy fraction required for a given manifold pressure. Calculations have also been carried out for methanol, and ethanol and methanol–water mixtures

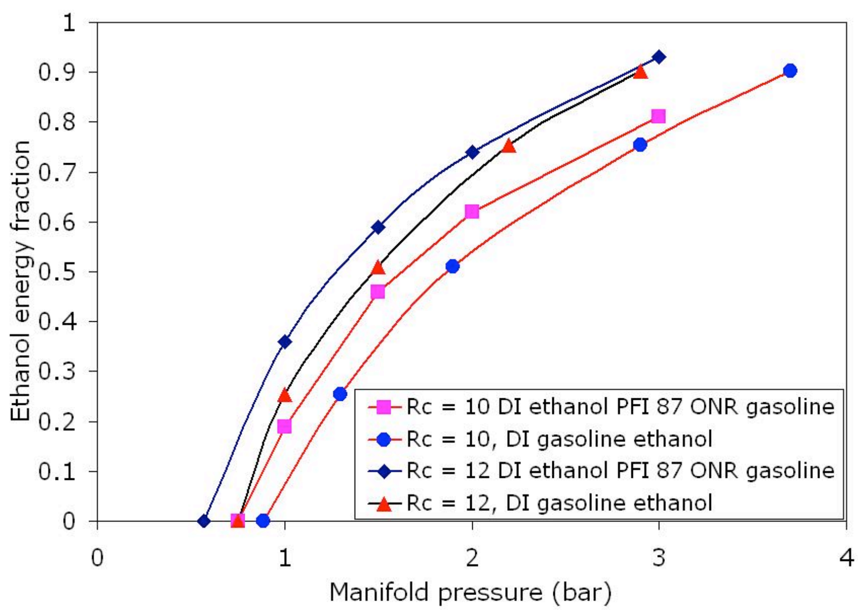

Figure 2. Model calculation of required directly injected ethanol fraction (by energy) for knock suppression as a function of inlet manifold pressure, at low engine speed, for compression ratios of 10 and 12, with either direct injection or port fuel injection of gasoline. Spark retard not included. (3).

The MIT and EBS work also included investigation of ways to use spatially and temporally optimized direct injection to increase the knock suppression effect for a given amount of alcohol.

Ford Motor Company has performed tests on three engines and has also done computer simulation work. (6,7,8) In the heavy-duty vehicle arena, a joint simulation study of alcohol boosted gasoline engine use has been carried out by Volvo Powertrain/Mack in collaboration with EBS. (9)

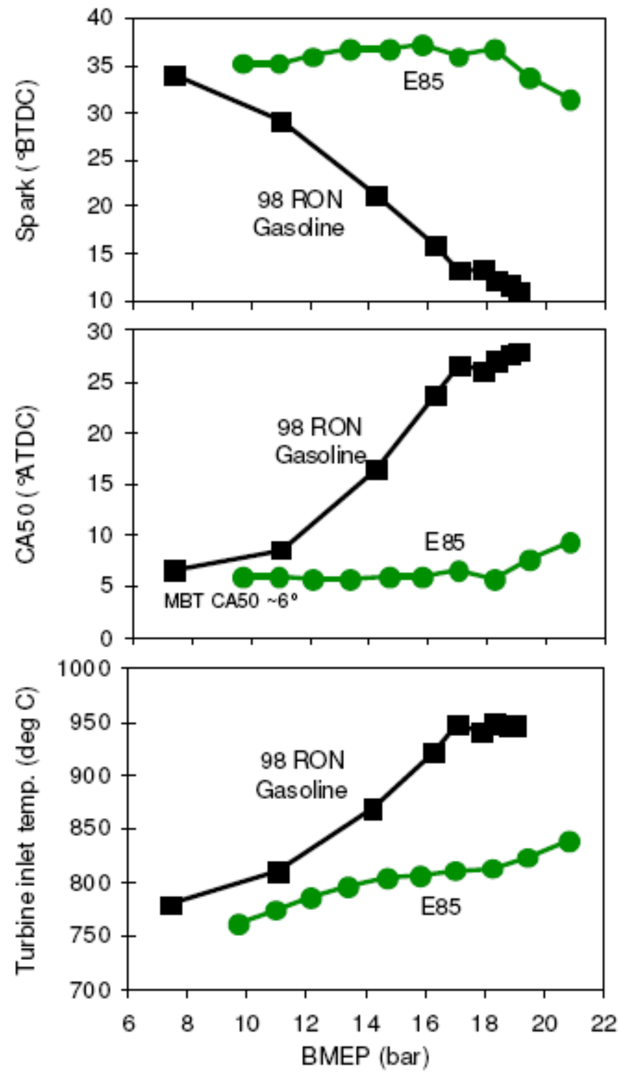

Figure 3. Experimental measurement E85 vs gasoline BMEP sweeps at 2500 rpm in a modified 3.5 liter GTDI engine (6).

Ford's engine tests were initially carried out in a modified 3.5 liter GTDI engine. (6) Tests were carried out at compression ratios of 9.8 and 12. The tests involved direct injection of E85 and port injection of gasoline. They showed a substantial increase in knock resistance that was consistent with the MIT/EBS models and the potential for alcohol boosted gasoline engines to provide an alternative to diesel engines. Figure 3 shows the higher pressures allowed by direct injection of E85 relative to direct injection of 98 RON gasoline without spark retard. For direct injection of gasoline, above 8 bar BMEP, spark retard is needed to prevent knock. With E85, knock free operation without spark retard extends to at least 18 bar (where spark retard is used to control peak cylinder pressure to prevent damage to the engine).

In a DOE cost-share project Ford, in collaboration with AVL, tested direct-injection E85 port-injection gasoline operation in a single-cylinder engine and in a 5 liter engine with a high pressure block. A preliminary Ford -AVL simulation for a 5 liter dual fuel engine showed that an increase in compression ratio of 3, along with controlling combustion phasing (spark retard) could provide an efficiency gain of around 13% over a 5 liter GTDI engine. This simulation is shown in figure 4. The E85 requirement for a metro-highway drive cycle was one gallon for every 530 miles. Use of an alcohol-water mixture or methanol would reduce the anti-knock fluid requirement to around one gallon for every 1000 miles, comparing favorably with a urea consumption of 860 mpg.. Further reduction in anti-knock fluid consumption could be obtained by use of direct injection of gasoline. Figure 4 also shows additional capability for hill climbing relative to GTDI due to the higher torque capability. The higher torque capability could alternatively be used to provide an additional vehicle efficiency gain by engine downsizing.

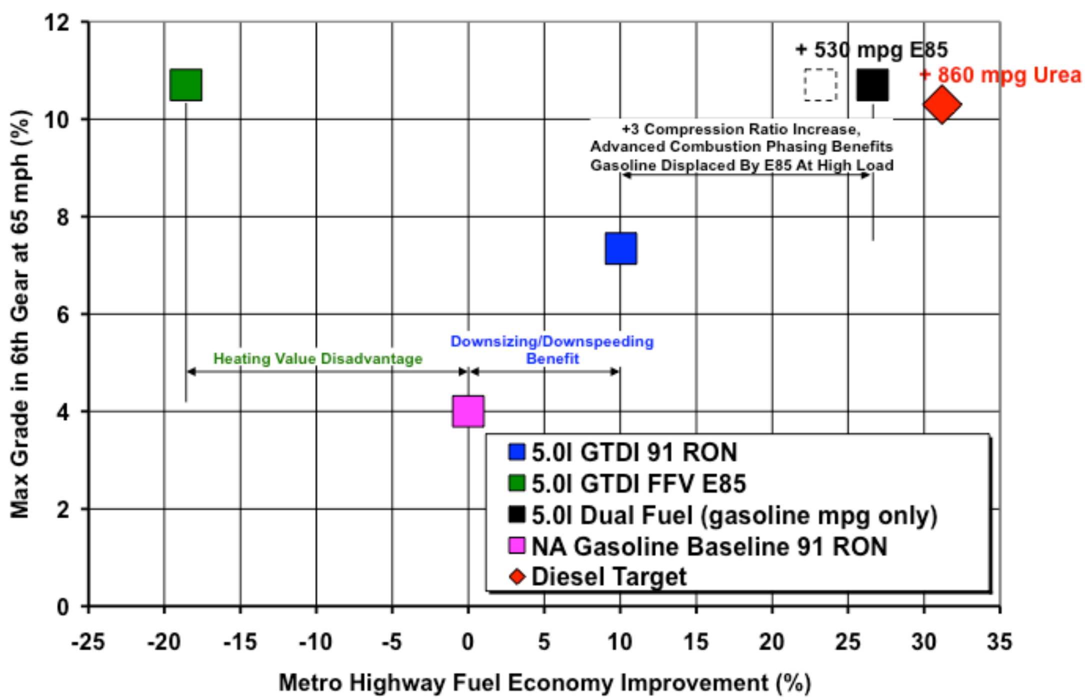

Figure 4. Cycle Simulation Results: Dual Fuel Optimized E85 Engine vs. Competitors – F-Series pick-up truck. Preliminary Results Based on Estimated Fuel Maps. (7) The white square represents the gasoline fuel efficiency improvement. The fuel efficiency improvement for the diesel engine is about 28% when corrected for the higher fuel density of diesel relative to gasoline and does not include the additional energy requirement to offset diesel exhaust aftertreatment losses.

Figure 5 shows BMEP and brake thermal efficiency at full load in the 5 liter engine with a compression ratio of 9.5 and a high pressure engine block. This data showed that use of directly-injected E85 provided a 75% increase in BMEP relative to a direct-injection gasoline engine operated with a stoichiometric fuel/air ratio and a relative increase in brake thermal efficiency of around 13%. Higher brake thermal efficiency could be obtained by higher compression ratio operation, resulting in the alcohol boosted turbo engine providing a relative increase in efficiency of around 20% compared to a GTDI engine.

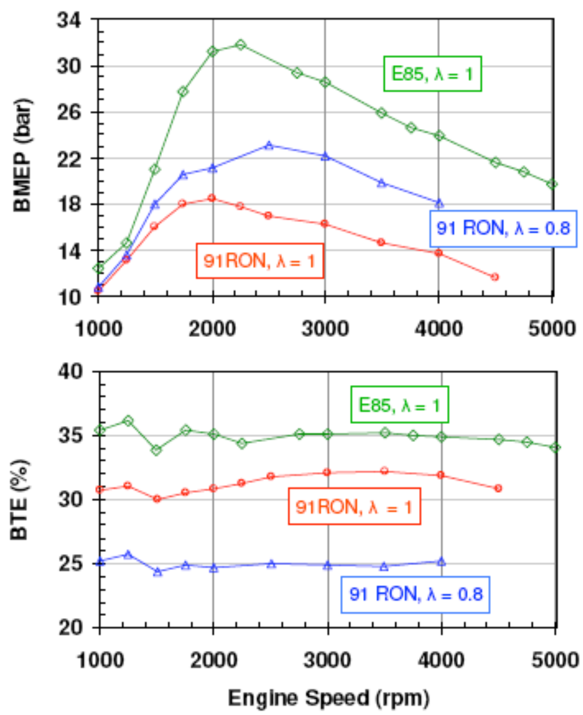

Figure 5. Multicylinder engine full load comparison between alcohol boost (E85) and GTDI (gasoline) at compression ratio of 9.5 (8)

Ford work has also shown that a substantial decrease in alcohol consumption can be obtained by spark retard. A temporary increase in spark retard can be a very effective way to keep alcohol consumption low during prolonged high torque operation such as during towing. Figure 6 shows how the E85 consumption can be cut by a significant factor by increased spark retard (with some reduction in efficiency). The reduced efficiency of an alcohol boosted turbo gasoline engine when towing would still be significantly greater than that of a GTDI engine.

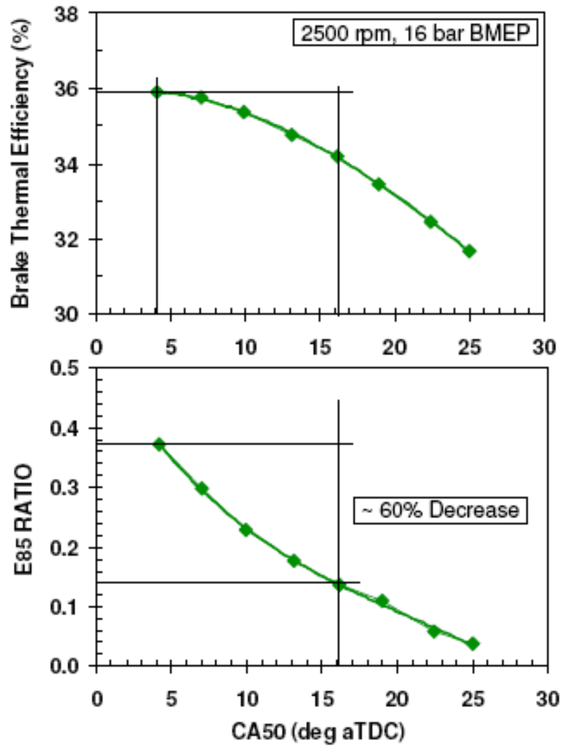

Figure 6. Dual fuel engine: effect of combustion phasing on E85 consumption for high load conditions. (8)

Computer simulations of use of an alcohol boosted gasoline engine to provide an alternative to a 11 liter heavy-duty diesel engine were carried out by Volvo Powertrain/Mack and EBS. The simulations showed that a 7 liter alcohol boosted engine compared favorably with the larger diesel engine. These simulations were carried out for different ratios of torque to the maximum torque at intermediate engine speeds. Brake thermal efficiency and alcohol consumption is shown at each point. Mild spark retard is used to reduce the alcohol consumption by around a factor of two relative to the case with no spark retard. Figure 7 shows the results for methanol. When E85 is used, the volumetric consumption of alcohol is close to a factor of two times greater than for methanol.

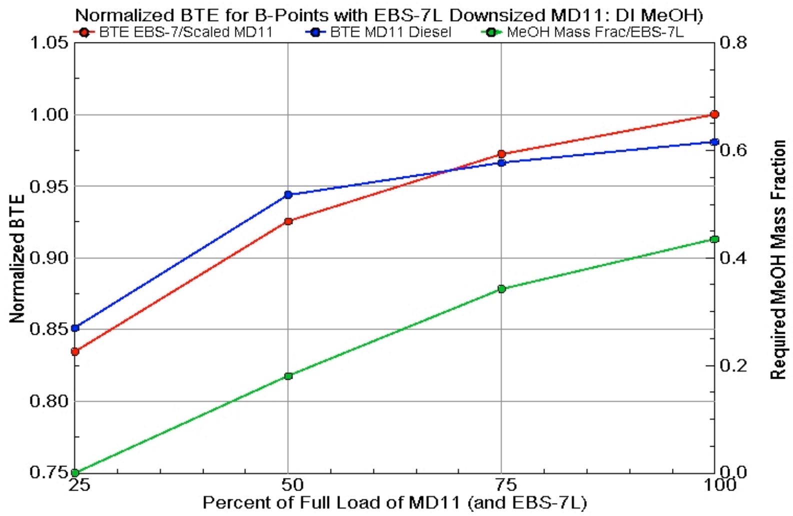

Figure 7. Normalized BTE and methanol fraction (by mass) as a function of percent of full load and middle-speeds for the baseline MD11 engine and a downsized alcohol boost turbo 7 liter engine. (9)

EBS estimates that for a light-duty truck, the incremental cost of an alcohol boosted engine plus exhaust treatment is about $4,000 less than the incremental costs for a diesel engine with the presently required exhaust emissions control. For a heavy - duty long-haul truck the cost savings are estimated to be around $15,000. These cost savings would represent a substantial percentage savings of the cost of a diesel engine plus exhaust treatment system.

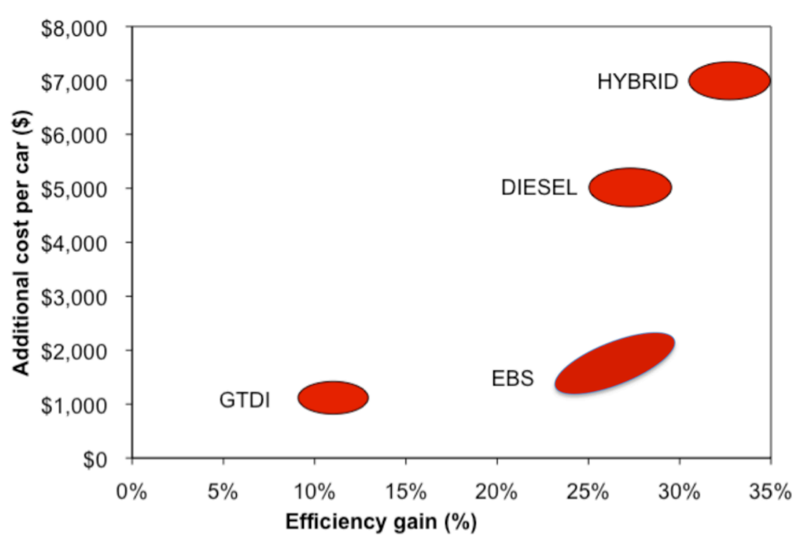

Figure 8. Illustrative incremental cost vs efficiency gain (light-duty truck). Baseline is port-fuel-injected naturally-aspirated engine. Alcohol boosted engine is represented by "EBS" oval

Relative to GTDI in light-duty trucks, an estimate for the additional cost of an alcohol boosted engine with diesel-like efficiency and torque is $800 - $1000. Of this, $300 is for the extra fuel tank and injection system, and the remainder for the high pressure engine block. Based on these numbers and a 15% - 20% efficiency gain relative to a GTDI engine, the additional cost per percent efficiency gain is $40 - $65.

Figure 8 shows EBS estimates of efficiency gain vs incremental cost for a light-duty truck for an alcohol boosted engine (the "EBS" oval in the figure) in comparison to a GTDI engine, a diesel engine, and hybrid powertrain. The efficiency gain and incremental cost are relative to a conventional naturally-aspirated port- fuel-injected engine. The efficiency gain is for the combined city–highway drive cycle.

Challenges

The main challenges for the alcohol boosted gasoline engine are related to the inconvenience of periodically refilling the alcohol tank. Factors that influence this challenge are the availability of alcohol fuel or an alcohol–water mixture, and the frequency of refill required. The improved efficiency and performance must justify this inconvenience to the driver. And the improved efficiency and performance/inconvenience tradeoff must be compared to other technologies for obtaining these benefits.

The use of urea for diesel exhaust treatment in light-duty vehicles (both in trucks and in cars) indicates that drivers are willing to accept the inconvenience of using an additional fluid in order to obtain efficiency and performance benefits. The availability of alcohol for alcohol-boosted engines is likely to be substantially greater than that of urea for urea-SCR diesel exhaust treatment. For typical driving the amount of alcohol needed is similar to that of urea. If alcohol-fueling pumps are not available, alcohol or alcohol–water mixtures that are similar to windshield washing fluid could distributed in a manner similar to the system used to distribute windshield cleaner and could be widely available at the same locations: service stations, convenience stores, jiffy lubes, garages and dealers. Alternatively, the alcohol refill could be effected at public E85 stations, where available, or by E85 pumps at dealers or at central fleet refueling stations.

The anti-knock fluid requirement for typical light-duty vehicle driving could be limited to around 1% of the gasoline requirement. For a car with a fuel economy of 40 mpg, a 1% requirement would be 1 gallon every 4000 miles. With a 4 gallon alcohol tank the refill interval would be around once every 16,000 miles. For a light-duty truck with a fuel economy of 25 mpg, the refill interval for a 2% requirement would be 1 gallon every 1200 miles and with a 8 gallon tank the refill interval could be around once every 10,000 miles. The effect of more aggressive driving in increasing the alcohol consumption could be reduced by optional use of premium gasoline, which could reduce the alcohol consumption by around a factor of two, or by increased spark retard.

Prolonged driving at high torque in a light-duty truck would require substantially more alcohol consumption without an increase in spark retard. However, with temporary use of additional spark retard (accepting its resulting decreased fuel efficiency) the volumetric use of an alcohol –water mixture could still be kept to a modest fraction of gasoline use. For example, the alcohol –water mixture consumption could be kept at around 5% of gasoline use based on the discussion in the previous section. For 20 mpg operation, the alcohol use would be around 1 gallon every 400 miles and the refill interval would be around 3200 miles for an 8 gallon tank. This range could be extended by a factor of two by using a larger or additional tank. The combustion retard to reduce the alcohol use to this level would be around 20 degrees and would reduce brake thermal efficiency for a high compression ratio engine to around 30%. This brake thermal efficiency would still be greater than that of a GTDI at high load.

In addition, for both typical light-duty vehicle driving and prolonged high torque operation, control strategies could be implemented to reduce alcohol consumption with some reduction in vehicle performance to avoid running out of alcohol. If the vehicle were to run out of alcohol, it would be drivable albeit at significantly reduced maximum torque and power capability.

For light trucks where comparable torque and efficiency to diesels can be realized, the extra fluid refill requirement would be comparable to that of urea-based emission–controlled diesels while providing the substantial benefit of lower cost, lower emissions and more power. In contrast to diesel vehicles using urea, an alcohol boost vehicle could still operate if there were no alcohol, albeit at lower performance, whereas diesel engine operation must be disabled if urea refill does not occur within a given period of time.

For cars and light duty trucks there is a range of efficiency benefit/additional fluid inconvenience tradeoffs. An alcohol boosted turbo gasoline engine would provide a means to fuel economy in a gasoline engine light duty vehicle approaching that of a hybrid without the additional cost of of the hybrid powertain; the inconvenience is the addition of a gallon of anti-knock fluid every few thousand miles.

For medium and heavy-duty vehicles with substantial operation at lower relative torque levels (*e.g.* urban delivery trucks) the alcohol boost requirement is comparable to the urea use now implemented in diesel engine vehicles. For heavy -duty vehicles used for long-haul trucking the alcohol requirement would be larger. It would be a considerably greater fraction of gasoline use (*e.g.* 25%) and pump fueling of E85 (or perhaps methanol) would be required.

In the case of reliance on pump fueling, the provision of E85-gasoline flex fuel capability (or possibly gasoline–ethanol–methanol tri-flex fuel operation) where alcohol is used in the main tank as well as the secondary tank is a natural option and could provide additional benefits if oil-derived fuel prices exceed alcohol fuel prices.

Flex fuel alcohol boosted gasoline engines could be employed in long -haul trucks used between hubs with their own fueling capability as an alternative to diesel trucks.

Findings:

- Engine tests and computer modeling indicate that direct injection of alcohol enables knock-free operation of gasoline engines with a stoichiometric fuel/air ratio at turbocharged engine manifold pressures of some 3 bar along with a compression ratio approaching 14. In comparison a GTDI engine operated with regular gasoline has knock-free operation with a manifold pressure of around 1.8 bar at a compression ratio of 10.

- This increased compression-ratio and turbo-boost pressure operating space makes it possible for gasoline engines to provide several combinations of improved efficiency and performance benefits. A high pressure block is needed for the greatest benefit. An alcohol boosted gasoline engine with a high pressure block can provide diesel –like efficiency and torque.

- The fuel efficiency provided by an alcohol boosted turbocharged engine with a high pressure block is 15% or more greater than a GTDI engine over the light-duty vehicle driving cycle and is 25-30% greater than a naturally-aspirated gasoline engine.

- Relative to a diesel engine, an alcohol boosted gasoline engine with diesel like efficiency and torque can generate substantial cost savings due to its much less expensive exhaust treatment system and less costly fuel injection system. It can also provide greater power (50% or more) and has greater potential for likely further required reductions in emissions.

- For light-duty vehicles, the incremental cost per percent of efficiency gain is around one third that of diesel and hybrid alternatives.

- The alcohol could be E85 or M85 provided by a pump, or in the form of an alcohol–water mixture like windshield washer fluid.

- For typical light-duty vehicle driving, computer modeling and engine tests indicate that the alcohol requirement for an alcohol boosted engine with diesel-like efficiency can be limited to around 1-2% of gasoline use. The refill interval can be once every 10,000 miles, similar to the case for urea refill with today's diesel.

- Alcohol consumption during prolonged high torque operation in towing can be kept at a modest level (around 5% of gasoline consumption) by increasing spark retard. The degraded engine efficiency could still be greater than a GTDI engine with fuel enrichment.

- Alcohol boosted gasoline engine technology can also provide benefits in light duty engines with conventional blocks. The compression ratio in a turbocharged engine could be increased from 10 to 12 thereby providing a 5 - 10% increase in efficiency relative to a GTDI engine (including the additional downsizing benefit from higher compression ratio). Another option is to use port fuel injectors for both the alcohol and gasoline in a low-cost turbocharged engine that provides a 15 - 20% increase in efficiency relative to a naturally-aspirated engine.

- For a heavy-duty vehicle used for long-haul trucking, the engine plus exhaust system cost could be substantially lower than a diesel engine (a cost reduction of around $15,000 is likely) and the power can be increased by around a factor of two. The alcohol consumption would be on the order of a quarter of the gasoline requirement thereby necessitating alcohol pump fueling. An alcohol boosted flex fuel heavy-duty vehicle could be suitable for heavy-duty vehicles that are employed in hub-to-hub freight operations.

- Alcohol boosting can also be used to improve the efficiency and performance of flexible-fuel alcohol-gasoline engines. Automatic refill of the secondary tank every time that the main tank is filled with alcohol can reduce or eliminate the need to separately refill the secondary tank.

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