Interim Report

Assessment of Higher Efficiency Options For Alcohol Fueled Vehicles[+]

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I. Background

Methanol has been used as a transportation fuel in US and in China. Flexible fuel vehicles and filling stations for blends of methanol from M3 to M85 have been deployed. It did not become a substantial fuel in the US because of its introduction in a period of rapidly falling petroleum price which eliminates the economic incentive, and of the absence of a strong methanol advocacy. Methanol was then displaced by ethanol as oxygenate of choice in gasoline blends. Nevertheless, these programs have demonstrated that methanol is a viable transportation fuel.

Methanol and ethanol could provide a near term, economically attractive alternatives to oil-derived gasoline for light vehicles in the US. These alcohol fuels can be produced from shale gas on energy-based cost that is competitive with oil-derived gasoline. They can also be produced from various biomass feedstocks and waste. (At MIT, under sponsorship from DOE/ARPA-E and the Tata Foundation, we have been working in a program that will economically convert natural gas at well-sites into methanol. The program has succeeded in providing proof of concept, and we are in the process of designing a demo plant capable of handling about 300,000 scf per day of natural gas, making about 1500 gallons of methanol per day.)

The economic attractiveness of alcohol fuel can be increased by use in spark ignition engines that make use of their special properties (high flame speed, high octane) to substantially increase the efficiency relative to conventional gasoline engines. These properties can increase the efficiency by 20 -30% .relative to a standard port fuel injected gasoline engine by optimized use of existing engine components.

We have assessed the options for introduction of methanol into the present fleet, mostly the implications for existing vehicles.

II. Optimized tuning of existing engines

We have extensively investigated the performance of methanol-assisted engines. The work has been done mostly for high methanol concentration fuels which would be used in flex fuel vehicles. We have used a relatively small, 4 cylinder engine, as the basis of the work. However, we have done extrapolations so that we can make comments on the performance with larger 6 and 8 cylinder engines used for light duty applications.

a) 4-cylinder engines

The advantages of the use of methanol in existing engines can be associated with 3 of its properties:

- Lower combustion temperatures, which result in decreased heat transfer between the charge in cylinder and the cylinder walls. The lower combustion temperature are due to

    a. decreased temperature of combustion
    b. increased heat capacity of methanol
    c. increased heat of vaporization of methanol.
- Faster flame speeds, allowing more constant-volume (isochoric) combustion
- Higher octane, which increases suppression of knock and thus enables improved performance and elimination of spark retard.

Higher engine performance (mostly described in terms of efficiency in this report) can be achieved by intrinsic properties of the fuels, as described above, with no changes to the operation of the vehicle. Or it can be obtained by using different software in the computer, adjusting the parameters (such as spark timing and valve timing), which requires re-calibration of the engine.

In this work, we also describe why there is quite a spread of results of different investigators.

We first investigate conventional, present-day gasoline powered vehicles fueled with methanol. This approach is easiest to implement and has the potential for the largest near term impact, by switching present day vehicles from gasoline to methanol. This approach makes use of the intrinsic fuel properties, while keeping the engine parameters and setting (*i.e.*, the calibration) constant. In this case, only the temperature effects and the flame speed are applicable. Spark and valve timing are held constant. Later in this report we will discuss a second approach, when the engine controls (spark and/or valve timings are adjusted), requiring changes in the software settings (calibration). And finally there is a last case, when the engine geometry and the setting in the software are also adjusted. We investigate these opportunities sequentially below.

In this report we only consider port fuel injection, as the majority of vehicles on the road use port injected, naturally aspirated engines rather than direct injection.

We also investigate the implications for both older engines (with relatively primitive combustion) and newer engines, with improved designs. In this case, the main difference is the turbulence in the cylinder and the location and strength of the spark, which results in faster combustion, even with gasoline.

1) Intrinsic fuel properties.

We have made the calculations assuming a neat methanol fuel (that is, 100% methanol). The potential advantages of using methanol are highlighted with this assumption. As the fraction of gasoline in the fuel increases, the results need to be adjusted accordingly. The advantages would be modestly reduced for M85.

As much as possible, we have tried to benchmark the results to experimental results. In particular, work carried out at University of Ghent on several engines as well as at MIT on an ECOTEC engine have been used to benchmark the models [J. Vancoillie, L. Sileghem, M. Van de Ginste, J. Demuynck, J. Galle and S. Verhelst, *Experimental Evaluation of Lean-burn and EGR as Load Control Strategies for Methanol Engines*, SAE paper 2012-01-1283].

2) Peak Power

The maximum power that the engine can generate depends on whether the existing engines are knock limited at the higher power. Some older naturally aspirated, port fuel injected engines are not knock limited and to do not use spark retard to enable higher peak power. Knock is prevented by a limit on compression ratio. These engines also do not generally have a structural limitation on peak power.

The calculations have been performed using GT Power, from Gamma-Technologies. GT Power can not be used for predicting the actual performance, but it can be used to investigate the sensitivity of the model to changes in operation, which has been benchmarked to experiments.

Our results for peak torque (measured as BMEP, or Brake Mean Equivalent Pressure, a measure of the engine capability of performing work that is not dependent on the size of the engine) for engines that are not knock limited, and thus do not have spark retard at conditions of high load, are shown in Figure 1. If the engine is not knock limited, higher power is available by the increased volumetric efficiency due to the cooler charge at condition of wide-open throttle. Also shown in Figure 1 are results for an engine that is knock-limited, with a spark retard of 10 crank angle degrees. The improvement in efficiency in this case is both by the improved volumetric efficiency, as well as elimination of the spark retard.

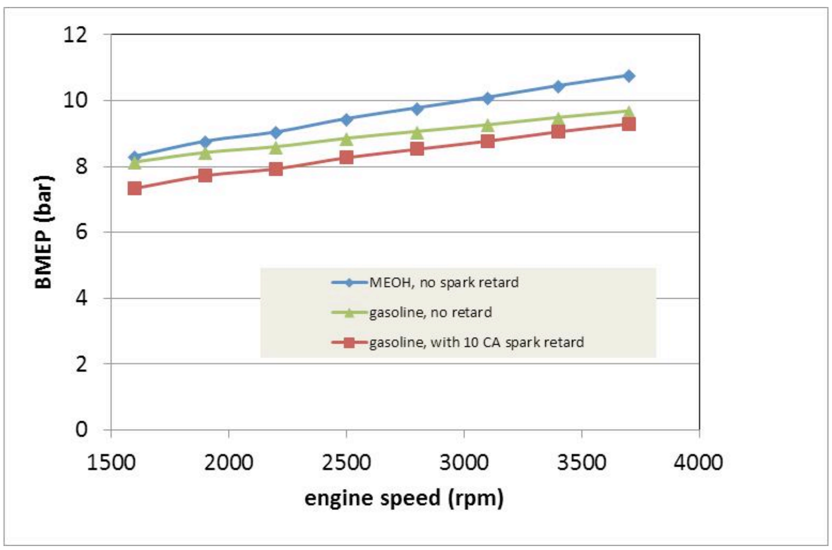

Figure 1a. Brake Mean Effective Pressure (BMEP) for an engine at Wide Open Throttle, as a function of engine speed, operating on methanol (w/o spark retard), on gasoline (w/o spark retard) and with gasoline (with spark retard, 10 CA degrees). The compression ratio is 10.3.

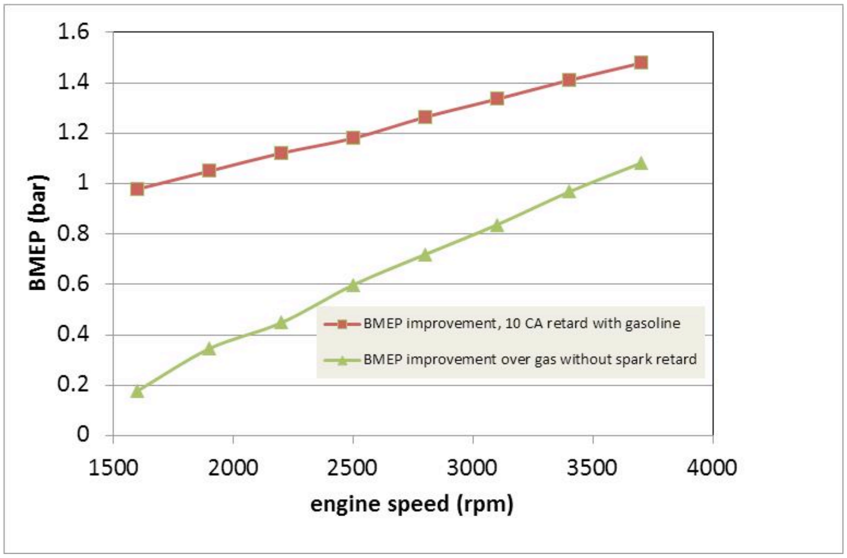

Figure 1b. Improvement in BMEP at WOT for the same conditions are Figure 1a.

The results for a naturally aspirated engine with a compression ratio of 10.3 are shown in figure 1. With no spark retard, the BMEP of the methanol powered engine is substantially improved over the gasoline engine.

The burn duration in the case of methanol has been decreased by 20%. In the case of gasoline, the burn duration has been assumed to be given by the following formula, determined by testing and benchmarking in an ECOTEC engine at MIT [Y. Jo, R. Lewis, J.B. Heywood and L. Bromberg, *Performance Maps of Turbocharged SI Engines with gasoline-ethanol blends: Torque, Efficiency, Compression Ratio*, Knock Limits, and Octane, presented at the 2014 World Congress, SAE paper, April 2014]:

$$\tau_{10\text{-}90} = 24.8 + .0028 * S - 8.06 * p_{\mathrm{inlet}}$$

where $\tau_{10\text{-}90}$ is the time required between combustion of 10% to 90% of the fuel), S is the engine speed (in rpm) and p_{inlet} is the pressure in the inlet manifold. Valve timing, as well as ignition timing, has been help constant. It is assumed that the engine is operating with WOT (wide open throttle operation).

In Figure 1, it is assumed that gasoline operates either at MBT (*i.e.,* no spark retard), or with 10 CA degrees of spark retard (to avoid knock at high torque, as is the case in some engines). Then the timing is adjusted for methanol (M100), at MBT; the spark timing at MBT changes due to faster flame speed and different air/fuel characteristics (temperature and composition). The BMEP (Brake Mean Effective Pressure) in the case of methanol is shown in blue, and it slightly increases with engine speed, with better breathing. The improvement in BMEP in the case of methanol is due to the cooler temperature, enabling slightly increased torques. In the case of higher rpm, the increase is substantial, about 10% increased BMEP (for the same conditions). The increased BMEP results in about 10% increase in both torque and power, at the higher engine speeds. Part of the increase is due to increased volumetric efficiency. Increased efficiency (from increased flame speed and from decreased cylinder wall cooling) also plays a minor role, as we will discuss later.

3) Engine efficiency in undiluted operation

The implication of the use of M100 on present engines is discussed in this section. As in the previous section, the spark timing is changed; however, valve timing is not adjusted.

We have evaluated the performance of the engine over the relatively limited space where the engine operates most of the time (on the US06 and the FTP 75 cycles).

We have used the same model above, at constant BMEP, in order to investigate the implication of using a different fuel (M100) as opposed to gasoline. We have used increased flame speed in the case of methanol (25% decreased burn duration) to simulate the effect of improved combustion properties of methanol. We illustrate two loads, 2.2 bar BMEP relatively low load (cruising at intermediate speed), and at high speed (high load, about 2/3 of full load).

Figure 2 shows the results for 2.2 bar. In the figure the thermal efficiency (on the basis of energy) is shown as a function of engine speed for both gasoline and methanol. In this case, the combustion properties as well as the optimization of the spark timing have been used to obtain the best efficiency in both fuels. The difference in the two fuels are due to the effects indicated before, including the re-optimization of the spark timing, which requires re-calibration of the engine. However, the valve timing is not adjusted.

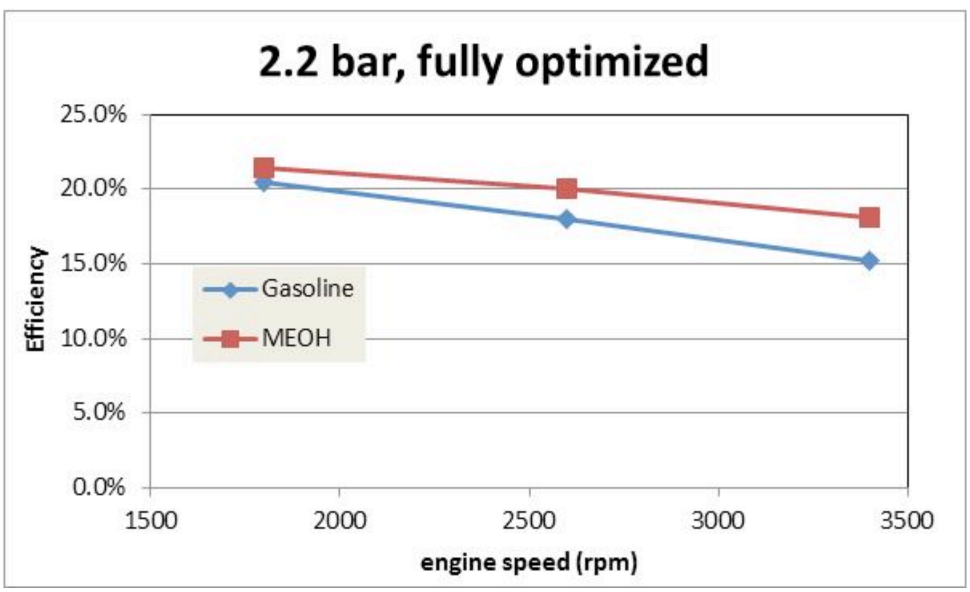

Figure 2. Efficiency of engine as a function of engine speed for the case of mid-load, for gasoline and for methanol; methanol case has been optimized for MBT timing.

There is a substantial improvement in fuel efficiency, without major modification of the engine. The improvement increases at the faster engine speeds. However, the improvement is due in part to adjustment of spark timing. Figure 3 shows the relative improvement in efficiency for the conditions of Figure 2, for the case of an engine running on M100 instead of gasoline (without adjustment of spark timing), and the additional improvement in efficiency due to adjustment of the spark timing with M100. The relative change in efficiency is defined as the change in efficiency over the efficiency of the case with gasoline. It should be noted that bulk of the improvement is due to the lower temperatures in cylinder and the faster flame speed; about 1/4 to 1/3 of the improvement is due to improved spark timing.

The constant spark calculations in Figure 3 are obtained by adjusting the combustion timing with gasoline so that it is at MBT. The same sparking conditions are then used to calculate the impact of methanol, shown in Figure 3 as "constant spark." The additional gain in efficiency when the timing is adjusted in the case of M100 is indicated in the figure as "due to spark adjustment." The total improvement in efficiency is the addition of the two. The total improvement in efficiency can be substantial, on the order of 10%.

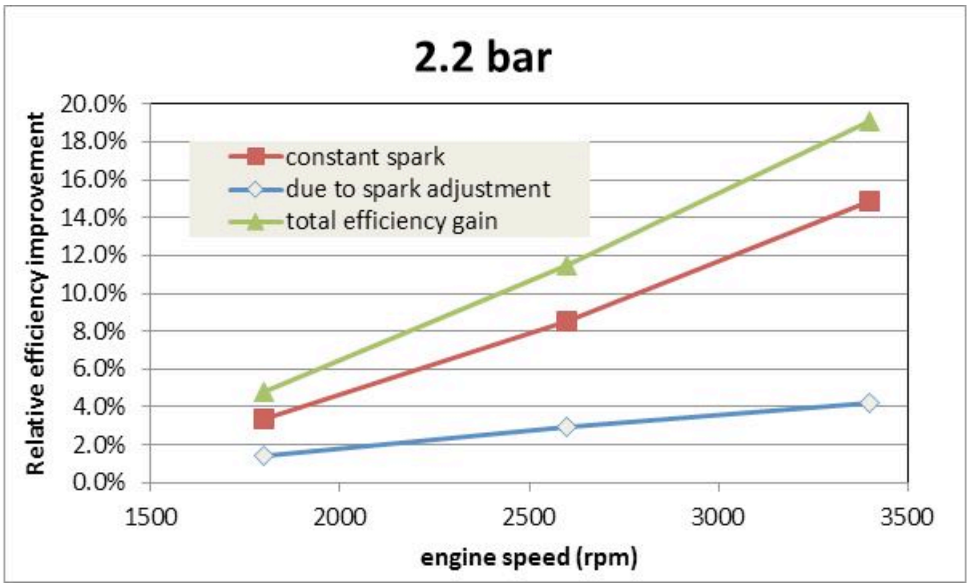

Figure 3. Relative change in efficiency when operating with methanol for case of constant sparking, and the additional change in efficiency when spark timing is adjusted to MBT timing.

It is interesting to note that in the case of methanol operation, at part load, the throttling losses are higher. As the temperatures are lower due to the large heat of vaporization of methanol and the higher heat capacity of the injected methanol relative to that of gasoline, the throttle needs to be closed more in order to maintain constant BMEP, increasing the pumping work. However, even when this effect is included, the efficiency in methanol is substantially higher.

Similar results are obtained for the case at higher load (7 bar). The efficiency for methanol and gasoline at the higher power are shown in Figure 4. In this case, the improvement in efficiency due to methanol is substantially lower than in the case at light load. The improvement in relative efficiency is about 8% across the engine map. Similar performance is obtained all the way to peak torque (BMEP). In addition, as indicated in Figure 1, there is substantially higher power generated by the engine, with slightly improvement in efficiency.

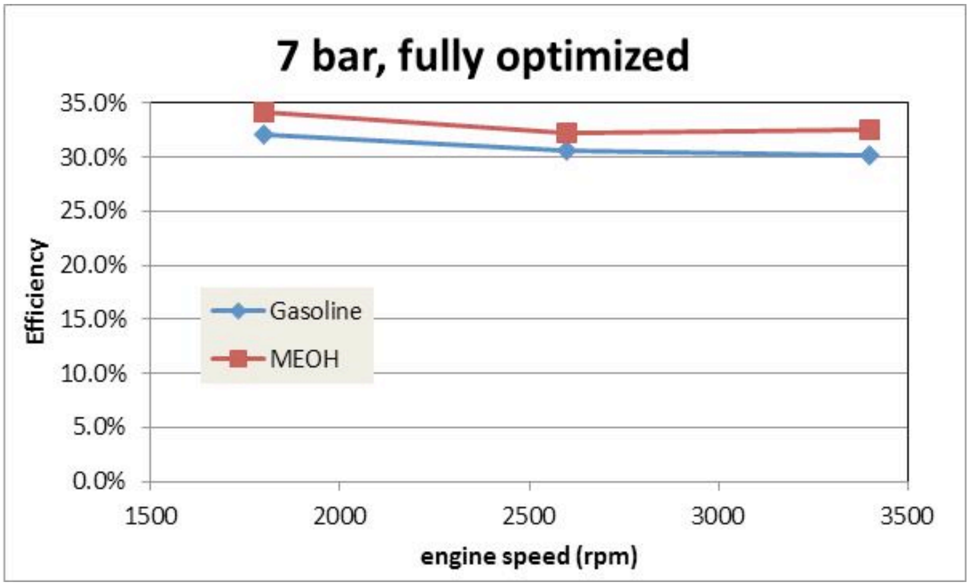

Figure 4. Same as Figure 2, but for higher BMEP (7 bar).

As in the case at lower BMEP, about 25%-30% of the improvement in efficiency is due to adjustment of the spark timing. In the case of methanol, because of the faster flame, less spark advance is required, and the reaction occurs faster, with shorter duration (approximating better to constant volume combustion).

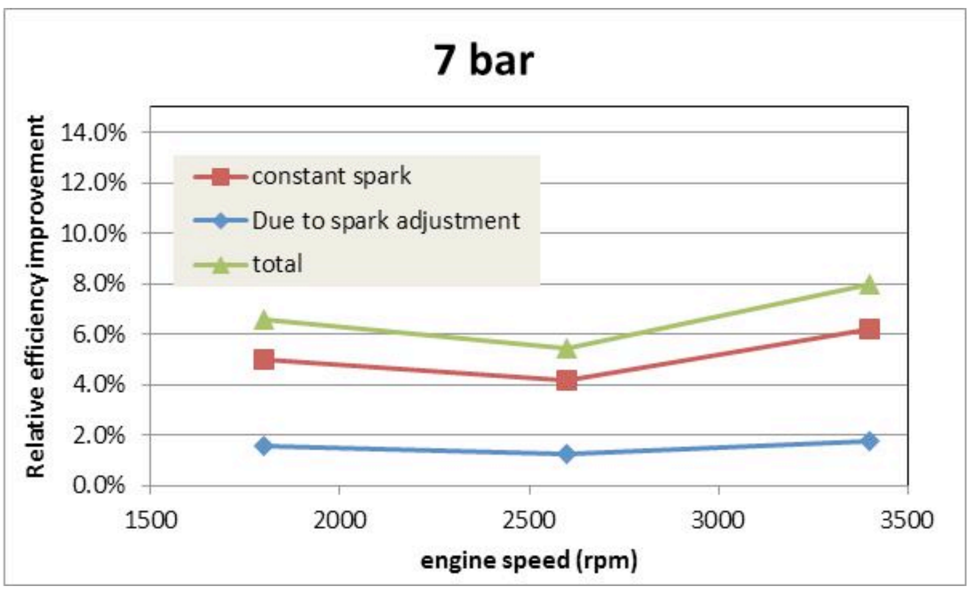

Figure 5. Same as Figure 4, but for higher BMEP (7 bar)

4) Engine efficiency in the case of dilute operation (EGR)

In order to minimize the pumping losses and to minimize the heat losses to the cylinder walls, diluted operation can be used. In this case, we have assumed the use of EGR (exhaust gas recirculation), as the alternative means of dilute operation (lean operation) requires the use of a different method of NOx control (three way catalyst is not effective with lean mixtures).

There are two basic methods for EGR: external EGR (with an external loop), and internal EGR, which can be achieved by adjustment of the inlet and exhaust valves. As the goal is to minimize changes in the engines, we will use internal EGR. Internal EGR can be readily achieved in production engines and in vehicles on the road, if they are equipped with variable valve timing. We assume that this is the case for the calculations in this section.

We have used calculations of flame speed as a means to estimate the flammability limits of the engine, and compared with experimental results in similar engines. We will in the near future carry out experiments in the ECOTEC engine to experimentally confirm the dilution limit mode. Our assumption is that if everything is the same (mostly flows), if the flame speeds for a given gasoline fuel and with a given dilution limit is the same as that for a methanol fuel with a different dilution are the same, then the burn duration (and COV, or Coefficient of Variability) are the same. We have checked the results with experimental results at stoichiometric combustion (with EGR) and the model behaves similarly.

Our assumption determines that the conditions for laminar flame speed for gasoline with 10% EGR and that of methanol with 35% EGR are similar. We have then used GT Power to calculate the conditions at ignition timing used in the flame speeds calculations, and CHEMKIN code to calculate the flame speeds at these conditions. We have used a reduced Curran model for combustion of gasoline, and the Marinov and Li models for the flame speeds of methanol.

Table 1. Laminar flame speed (cm/s) as metric to determine EGR tolerance: limits for gasoline and methanol

		gasoline	methanol
No dilution			
	laminar flame speed (cm/s)	55	67
EGR operation			
	EGR limit (%, by mass)	10%	35%
	laminar flame speed (cm/s)	25	25

Table 1 shows the results. The laminar flame speeds are about 50 cm/s for the case of gasoline and about 70 cm/s for methanol when running stoichiometric (and thus the combustion duration is reduced by ~25% in the case of methanol). During diluted operation, the velocities with 10% EGR with gasoline (dilution limit for gasoline) and methanol with 35% dilution are about 25 cm/s. It is the potential for increased dilution that offers substantial potential for improved vehicle performance with methanol.

For most of the engine map in the case of methanol (with the exception of operation at loads smaller than 1.5 bar BMEP), the diluted engine operates at WOT (Wide Open Throttle), that is, without throttling losses. The presence of the EGR also reduces substantially the heat exchange in the cylinder between the gas and the cylinder walls, as the combustion temperatures are lower. It is also likely that the NOx generation is substantially smaller, but we have no means to determine the nature of the losses.

The use of cold EGR has been used experimentally in methanol engines. Cold EGR is needed in turbocharged engines, which in the case of gasoline need lower temperature to protect the turbo, and the cold mass to prevent knock at higher temperatures. To our knowledge, hot EGR has not been, and in particular, heavy hot EGR at part loads. The use of hot EGR serves two purposes: it increases the temperature of mixture, which in turn results in increased EGR tolerance. Secondly, it also decreases the dilution required for operation at WOT, as the air/fuel/EGR mixture is slightly hotter.

We have thus adjusted the operation of the engine so that for the points of interest (above all but the lowest torques), it operates WOT.

The results of the model using GTP power are shown in Figures 6 and 7, again for light load (2.2 bar) and part load (7 bar). It is assumed that the burn duration in both cases is given by the $\tau_{10\text{-}90}$ formula above. Since it was not possible to operate with gasoline at WOT, the results are not compares to those of gasoline. WOT operation with hot EGR substantially increases the temperature at ignition time (increasing combustion stability, making up for the increased EGR). The efficiency in the case of light load increases by about 10%, while that at the heavier load (with reduced pumping losses due to the closer to WOT operation) improve by about 6%. Substantial efficiency gains are obtained in this manner.

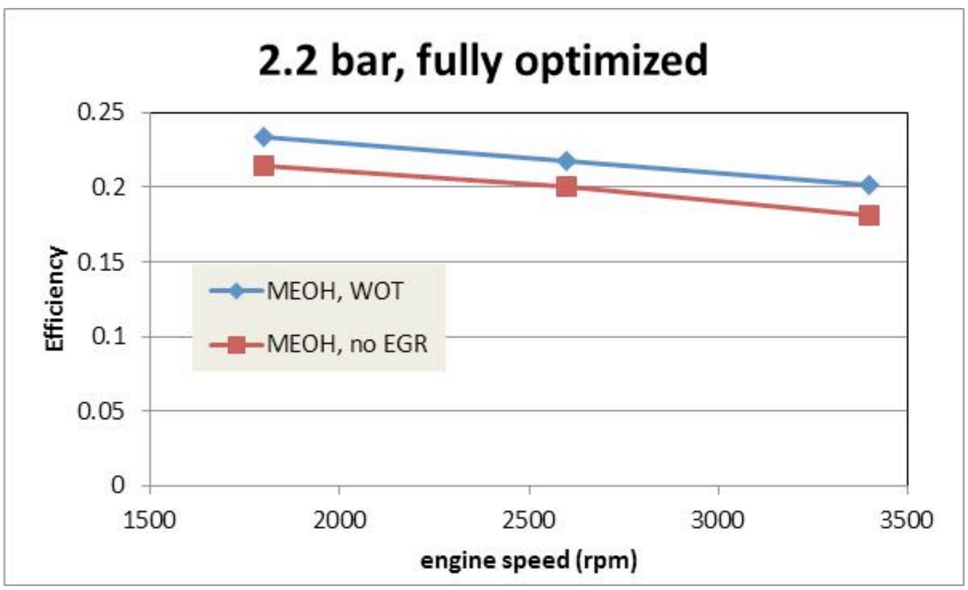

Figure 6. Comparison of light load operation with methanol, optimum spark timing, with and without hot EGR.

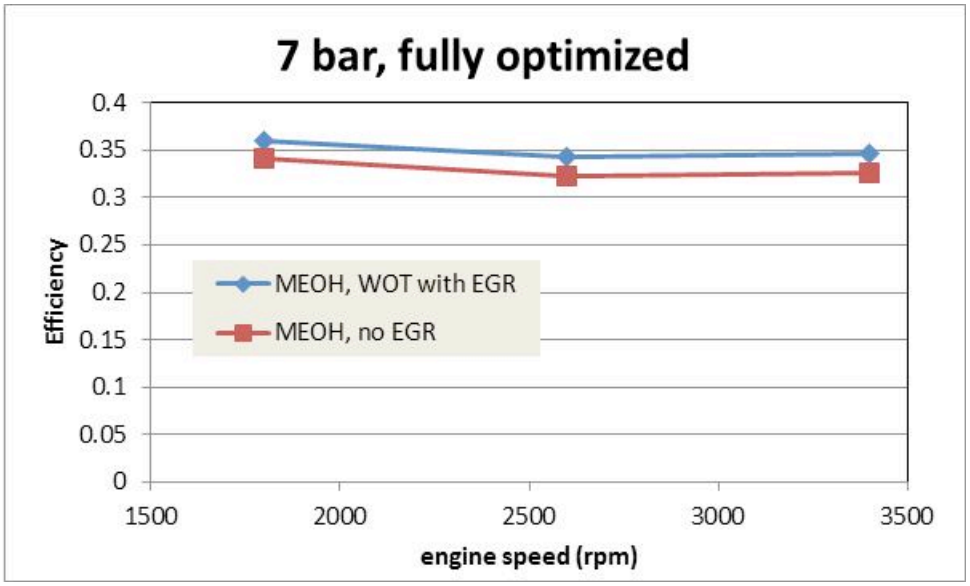

Figure 7. Same as Figure 6, but for higher load

It should be noted that the estimated improvements in efficiency with hot, internal EGR makes the case for experimental confirmation of this efficiency improvement. With colleagues working on a different projects we may be able to carry out some measurement using high blends of methanol with valve optimization (in particular, exhaust valve optimization), which should result in operation at WOT operation at part loads. We expect that these experiments would take place in a ECOTEC (GM) engine. which is not optimal for our purposes since it is set up with direct injection instead of port fuel injection.

5) Burn duration considerations

It is well established that methanol has higher flame speeds and thus shorter burn durations. A substantial fraction of the efficiency gain when using methanol is due to the faster flame speed. However, it is useful to determine the sensitivity of the studies to burn duration. That is, how large is the impact of flame speed on combustion of modern, high performance combustion engines?

We have estimated the impact of even shorter combustion duration, and determined that additional gains in efficiency are very small. That is, once combustion is fast enough, making it faster (as would be the case with methanol) does not result in improved efficiency. Figure 8 shows the results, with no EGR (*i.e.*, throttled operation).

It should be noted that once combustion is fast enough, making it faster does not have substantial impact on efficiency. This result has significant implications to the methanol/gasoline comparison. Modern engines have optimized combustion properties (cylinder motion induced through the use of multiple valves and optimization of valve opening and closing, location of spark, and others) that minimize the combustion duration. Faster combustion is obtained through improved modelling of the cylinder geometry and through careful engine calibration. Thus, the impact of switching from gasoline to methanol depends on the engine design and calibration. The same engine, in different model years, can have changed calibration and motion, which results in changing efficiencies. The impact on engine efficiency of switching to methanol, everything else being the same, could vary substantially, with larger efficiency gain in engines with less optimized combustion. The large difference in results from different authors on impact of methanol on their engines could be a result, simply, of the use of different engines. The more optimized engines showing substantially reduced efficiency gains that other less optimized engines. Typical combustion duration in present day engines is about 25 CA degrees. For older engines, it is closer to 30 CA degrees.

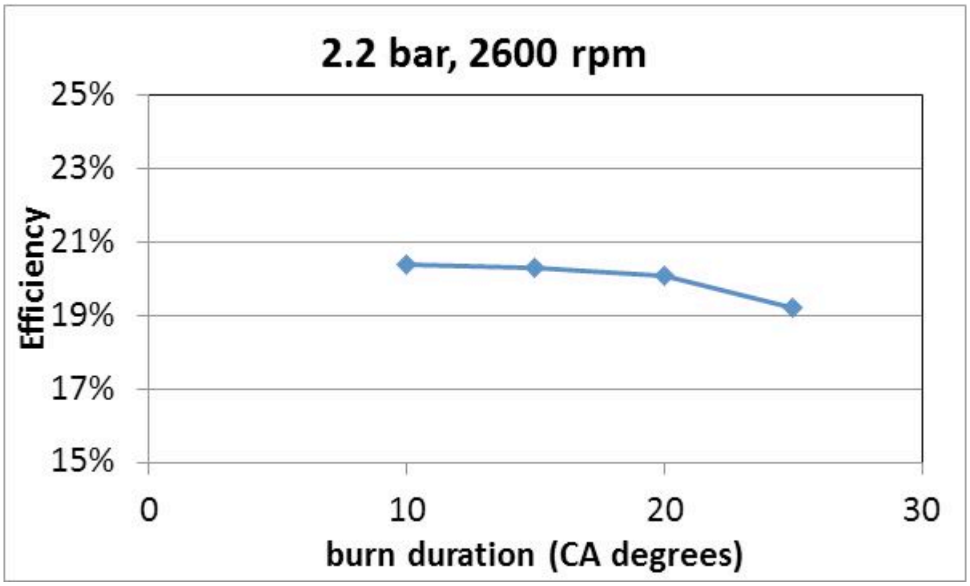

Figure 8. Impact of reduced burn duration on engine efficiency. Light load, mid speed.

b) Larger displacement engines

In the case of engines that have larger power to weight ratios, the engine performance is similar to that indicated above. The surface to volume ratio changes, but the details of the heat exchange are not clearly defined, as the motion of the charge in the cylinder can vary. In the case when the engine gets larger but the engine operates in similar mode, the heat transfer is relatively similar. Although there is lower surface to volume ratio and there is less turbulence, the combustion duration increases in general, resulting in similar heat transfer. Thus, the model that has been developed, although not absolutely precise, is useful to determine the trends of the different engines.

More important is the cycle. Larger engines with larger power-to-weight ratios would operate at lower torque than smaller, more loaded engines. Thus, the improvement in efficiency is substantially higher. We will describe the results of the cycle models when comparing different types of vehicles.

III. Vehicle simulations

In this section we investigate the vehicle implications of the use of gasoline and methanol with optimized MBT spark timing and methanol optimized including spark timing with EGR (valve timing).

We are starting to transition to the code Autonomie to perform the vehicle simulation calculations, but the calculations reported below were performed using the code ADVISOR from AVL. The results of the calculations for an older light duty sedan (such as the Toyota Camry) are shown in Table 2. Two drive cycles were used. A light-loaded urban driving cycle (FTP-75), with modest acceleration and prolong operation at light load. It should be noted that operation at light load, with gasoline, is very inefficient. Methanol allows for improved efficiency due to the effects discussed in the previous sections. However, the results in Table 2 with methanol require engine recalibration for meeting EPA requirement. That is, changes in the spark timing (for making use of the faster combustion from methanol) and/or changes in exhaust valve timing (for allowing dilute operation) requires recertification of the vehicle.

It is not clear to us how extensive the re-certification process needs to be. We are inquiring with colleagues in the OEM's as well as in their suppliers to determine the extent of the changes. We have been told that calibration of an engine requires a large manpower effort

Table 2. Energy efficiency (in %) of gasoline, methanol (spark optimized) and EGR diluted methanol (spark optimized) for two different driving cycles. Also provided is the relative efficiency improvement with respect to gasoline performance.

		gasoline	MEOH, no dilution	MEOH WOT with EGR
FTP 75		21.5	24.9	26.3
	relative improvement		16%	22%
us06		22.1	24.1	25
	relative improvement		9%	13%

For the larger vehicles, operating with similar weight-to-engine size ratios and with similar transmission, the model shows very similar performance than those indicated above. Slight changes due to changes in drag and rolling resistance exist, but they are outside of the precision of the model. More important is the impact of having an engine with higher specific power (*i.e.*, larger engine relative to weight). In this case, the engine operates at lighter loads that in the case shown in Table 2. Lighter load operation results in reduced fuel efficiency. However, the impact of methanol use in these cycles is larger.

In the case of Tables 2 and 3, there is little spark retard even in the case of gasoline (assumption). Including spark retard at high load to avoid know does result in substantial loss of efficiency. However, for both driving cycles, operation at high torque that may require spark retard is very limited, and thus does not have a large impact on the fuel consumption over a cycle and thus on the fuel efficiency numbers in Tables 2 and 3.

Table 3. Impact of increased power-to-weight ratio (30% increase with respect to Table 2).

		gasoline	MEOH, no dilution	MEOH, WOT with EGR
FTP 75		17.0%	20.5%	21.8%
	relative improvement		20%	28%
us06		18.4%	20.5%	21.6%
	relative improvement		11%	18%

It should also be noted that it is most useful to make relative comparison between the numbers in Tables 2 and 3, instead of the absolute numbers. The actual numbers are a strong function of engine calibration (including shifting points for the transmission). The engine calibration change from different OEM's and even with model years for the same OEM. One thing to note is that with improved engine calibration and drive to increased fuel economy, automakers have been steadily improving fuel economy, even with the same engine technology (assumed in this report to be naturally aspirated, homogeneous SI operation).

IV. Higher Compression Ratio

We have investigated the implications of higher compression ratio. Higher compression ratios are possible with methanol, but not with gasoline (unless with very aggressive spark retard, thereby reducing efficiency. Thus, increasing the compression ratio results in a dedicate fuel vehicle, as the vehicle will only operate at substantially reduced performance on gasoline.

The results in this section are in the absence of EGR, with the exception of minor valve overlap. Implementing EGR will further improve efficiency. The purpose of this section is to determine the potential of improved in efficiency due to compression ratio, and it is expected that the improvement due to EGR and higher compression ratio are additive. Furthermore, it is well known that increased compression ratio further increases dilution tolerance; thus it is possible that the improve in efficiency will be even higher than indicated in this section.

We have done calculations varying the compression ratio from 9.2 through 13. We think that increasing the compression ratio further results in very limited improvement in fuel efficiency.

In this case we have data obtained through a separate program, funded by the Department of Energy, investigating alternative fuels in a turbocharged engine (a 2 liter GM ECOTEC). We have been able to perform substantial benchmarking of the model with actual engine data. However, we should stress the fact that we have no access to the OEM calibration, and are using instead an alternative software to control the engine operation. Thus, the results obtained in that study may be different than the way the engine operates on vehicle.

Although the maps presented in this section were done for a turbocharged engine, the results are applicable to conditions where the inlet manifold are at or below atmospheric pressure. We limit the performance to those conditions.

The engine has been limited to about 100 bar and about 120 bar pressure + 3σ, which severely limits the operation. This is a concern on the methanol conversion to higher compression ratios, as they would have higher peak stresses at the high torques than those assumed by the manufacturer. Aftermarket engine modifications to increase the compression ratio in present engine would void vehicle warranty.

The performance of the engine has been determined through extrapolation, from data obtained at compression ratio of 9.2 the results are shown in Figures 9, 10 and 11, for compression ratios of 9.2, 11.5 and 13.5

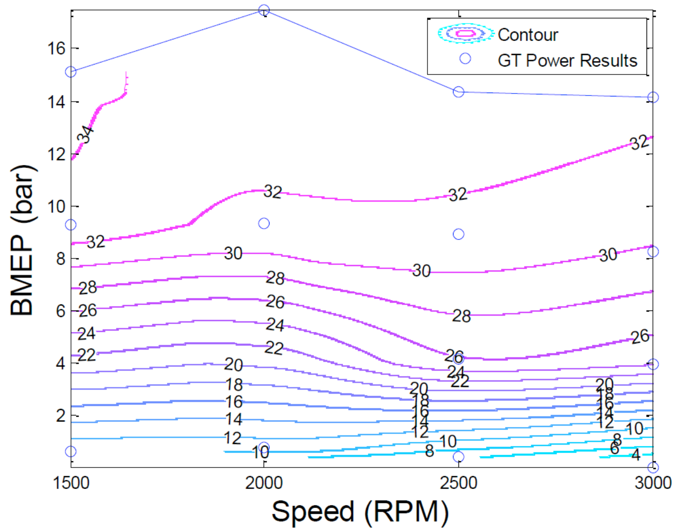

Figure 9. Efficiency through the engine map for a DI engine operating on gasoline, at a compression ratio of 9.2 (data benchmarked with actual engine operation).

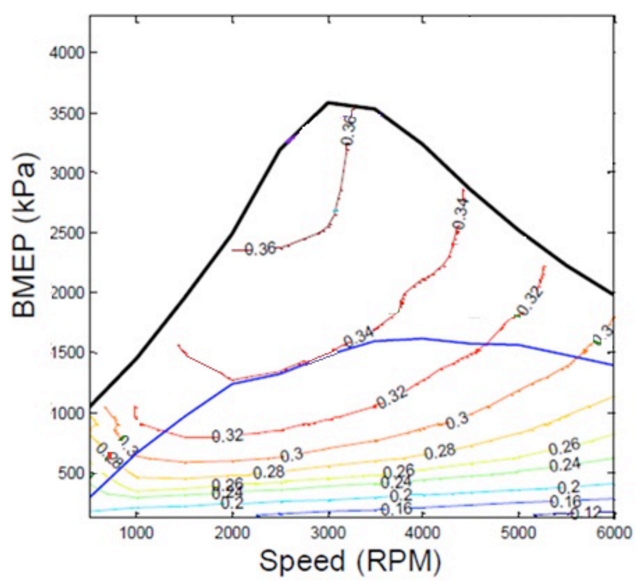

Figure 10. Engine efficiency across the engine map, for a DI engine with a compression ratio of 11.5 operating with gasoline, but assuming no knock. Knock limited (MBT timing) operation in gasoline (UT96) is indicated with the blue line for the conditions of this engine.

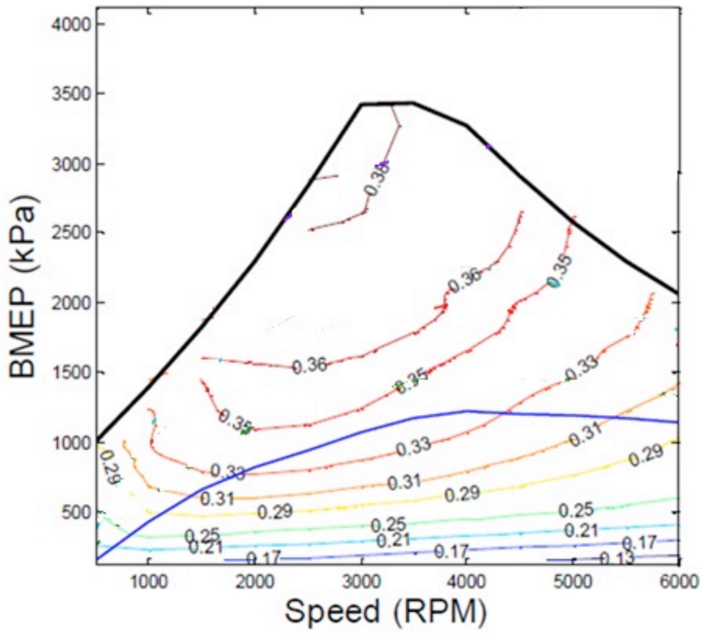

Figure 11. Same a Figure 10, but for a compression ratio of 13.5. Knock limited (MBT timing) operation in gasoline (UT96) is indicated with the blue line for the conditions of this engine.

Although the Figures were obtained for direct injection, it is possible to extrapolate the results to methanol engines, using the models derived above.

We have estimated the efficiency improvement due to the higher compression ratio, assuming that the engine can take the increased load. In principle, aggressive spark retard could be used at the highest loads to reduce the peak pressure, without substantial impact on the overall engine efficiency as engines do not operate for substantial time at conditions of high loads for the cycles under consideration.

The calculated efficiencies are shown in Table 4, for an engine using natural aspiration (that is, ignoring the part above the region of the maps in Figures 9-11 that require pressures higher than atmospheric in the inlet manifold. As above, it is most useful to use relative numbers, as opposed to absolute numbers in the comparison. Increasing the compression ratio increases the efficiency, as expected, but at a reduced rate at compression ratio higher than about 12.

Table 4. Efficiencies for two driving cycles and for three compression ratios

RC	FTP-75	US06
9.2	23.4	30.4
11.5	24.7	31.8
13.5	25.1	32.3

Using the data from the model, it is possible to determine the improvement in efficiency for the two cycles. Table 5 shows the information. Starting with a compression ratio of 10, increasing the compression ratio to 11.5 provides about a 4% increase in efficiency. Going to compression ratio of 13.5 increases the efficiency by about a couple percent more, indicating that the improvement of efficiency with compression ratio is levelling off at these compression ratios.

These increases of efficiency with increasing compression ratio could also be obtained in naturally aspirated , port fuel injection engines where methanol in used instead of gasoline and higher compression ratio operation is enabled by the higher knock resistance.

Table 5. Improvement in efficiency with increased compression ratio

Rc	UDDS	US06
11.5	4.1%	3.1%
13.5	5.8%	4.8%

V. Conclusions

In conclusion, substantial improvement on fuel efficiency could be obtained in present (5-10 years old) vehicles by substituting methanol for gasoline. Although the calculations in this report are for neat methanol (M100), the trends should apply to M85.

About 15% relative gain can be obtained compared to older engines with less optimized combustion than modern engines through fuel substitution and improved spark timing. An additional 5% can be obtained through the use of WOT operation introducing hot residuals (hot EGR) in the cylinder through adjustment of the exhaust valve timing. Increasing the compression ratios in present engines would further increase the efficiency by another 5%.

The gains depend on the baseline engine. More modern engine with optimized combustion in gasoline will provide smaller benefits from operation with methanol than older engines with slow combustion and lower knock tolerance. More studies of impact of hot EGR for improved combustion and EGR tolerance need to be performed.

Table 6. Summary of potential of different parameters, averaged over driving cycles

Parameter	Potential improvement	Cost	Re-certification?
Intrinsic methanol properties	~ 5-10%	low*	maybe
spark timing	~ 4%	0	yes
EGR /exhaust valve timing	~ 5%	0**	yes
Increased compression ratio	~ 5%	engine rebuild	yes

* May need modification of fuel delivery system

** Vehicle requires some form of variable valve timing

A summary of potential efficiency gains for different driving cycles is shown in table 6. It should also be noted that efficiency gains could be even higher for older large engine vehicles.

One powerful conventional tool not described in this report is the possibility of engine downsizing. Because the goal is to investigate potential in the present fleet, we have not addressed this opportunity. However, it has been demonstrated that diesel-like efficiencies are possible with aggressive downsizing/turbocharging when running on methanol.

An issue that has been raised about methanol operation is emissions during cold start. Although emissions from a methanol powered vehicle during warmed operation are lower than those of gasoline, emissions (in particular, formaldehyde) during cold start could be higher. There are means of addressing this possible issue; the assessment of them is outside the scope of the present work.

In summary, this assessment indicates that a 20-30% (depending on the driving cycle) increase in energy based fuel efficiency could be obtained in existing vehicles using methanol with modest engine changes. The high end of the range is for older vehicles with larger displacement engines and less optimized combustion. Substantial but somewhat lower efficiency increases should also be possible using ethanol. These increases in efficiency using alcohol may be particularly important in motivating alcohol use when fuel market conditions do not provide a significant price advantage of alcohol fuel relative to gasoline.