Evaluation of Homogeneous Charge Compression Ignition (HCCI) Engine Fuel Savings for Various Electric Drive Powertrains

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Abstract—The past couple of years have seen a significant increase in powertrain electrification to increase fuel displacement. Car manufacturers have been focusing on various powertrain configurations (e.g., parallel, series, power-split) and applications (e.g., Hybrid Electric Vehicles [HEVs], Plug-in HEVs [PHEVs]). In parallel, numerous engine technologies offer great potential from a fuel consumption point of view. One of them, the Homogeneous Charge Compression Ignition (HCCI) engine, is of particular interest due to its significant gains. This paper studies the fuel consumption potential of HCCI engines for numerous powertrain configurations, from conventional to HEVs and PHEVs. Both standard-drive cycles and real-world cycles are taken into account. Two vehicle control strategies, including one specifically tuned to maximize the benefits of HCCI operating modes, are considered and it is shown that conventional and mild hybrid powertrains benefit the most from the HCCI technology.

Keywords—HCCI, HEV, PHEV, Real World, Drive Cycle, Fuel Consumption.

1. Introduction

Homogeneous Charge Compression Ignition (HCCI) engines have captured car manufacturers’ attention because of the significant fuel efficiency gains that they achieve compared to spark-ignited (SI) gasoline engines. Improvements in automobile component controllers have solved some of the issues related to the difficult combustion control inherent to HCCI technology. In an HCCI engine, a homogeneous mixture of fuel and air is injected into the cylinder’s combustion chamber, typically at a high air-to-fuel ratio. The charge is then compressed until it auto-ignites, without the use of a spark, unlike SI engines. Due to the very lean combustion process, fuel consumption as well as emissions are greatly reduced. HCCI technology is being developed at a time when numerous electric drive powertrains have been developed and produced, such as those found in Hybrid Electric Vehicles (HEVs), thus providing the opportunity to combine HCCI with multiple vehicle architectures.

In this paper, we will first explain how the HCCI engine map was designed for simulation, and provide the main assumptions concerning components and the vehicle. In a second part, we will describe how, using the Powertrain Systems Analysis Toolkit (PSAT), Argonne National Laboratory’s vehicle modeling and simulation tool, various vehicle architectures were simulated (Conventional, HEVs, and Plug-in Hybrid Electric Vehicles [PHEVs]) with both a regular SI engine and an HCCI engine. Different control strategies were used for HEVs and PHEVs. Finally, the effect of HCCI engines was studied on Real World Drive Cycles (RWDC), for both a conventional vehicle and an HEV.

2. Assumptions

2.1. SI-HCCI Engine Map Development

High-fidelity engine models were created using GT-Power, a commercial engine cycle simulation tool developed by Gamma Technologies \cite{1}, which is part of their integrated multi-physics modeling environment, GT-Suite. The cycle simulation employs one-dimensional (1-D) wave dynamics for pipe flows and in-cylinder thermodynamics to predict engine combustion and performance. A complete model of a single-cylinder engine was built using geometric data from a typical 2.0L production engine. Standard valve lift profiles and experimental engine head flow data were also incorporated. The major engine specifications are summarized in Table 1.

Table 1: SI-HCCI Engine Geometry for Map Generation

<table>
<thead>
<tr>
<th>Engine</th>
<th>Naturally-Aspirated Single-Cylinder Direct-Injection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bore</td>
<td>86 mm</td>
</tr>
<tr>
<td>Stroke</td>
<td>86 mm</td>
</tr>
<tr>
<td>Displacement</td>
<td>499.96 cm$^3$</td>
</tr>
<tr>
<td>Con Rod Length</td>
<td>175 mm</td>
</tr>
<tr>
<td>Compression Ratio</td>
<td>SI 11.0:1</td>
</tr>
<tr>
<td>Fuel</td>
<td>Iso-octane</td>
</tr>
</tbody>
</table>

The lower compression ratio in the SI engine was required to reduce the likelihood of knock. Practically
speaking, different compression ratios can be achieved in the same engine using variable valve actuation strategies. The Atkinson or over-expanded cycle commonly implemented in HEV engines usually employs late intake valve closing to effectively reduce the compression ratio while still maintaining the higher expansion ratio based on the geometric design of the engine.

Submodels for combustion, heat transfer, knock, and nitrogen oxide (NO\textsubscript{x}) emissions were also implemented, to ensure predictability in the simulations. Combustion in the SI engine was modeled using the built-in GT-Power version of the classic turbulent entrainment combustion approach [2] originally proposed by Blizzard and Keck [3], and later refined by Tabaczynski and co-workers [4, 5]. The two-zone combustion model assumes a spherical flame front propagating into a homogeneous unburned mixture. It also assumes that turbulent combustion occurs in two steps: turbulent entrainment and subsequent burning. The mean turbulent intensity and length scale, calculated using a \(k - \varepsilon\) model, are used to determine the characteristic combustion time (from entrained to burned) and the turbulent burning velocity, which is assumed to be proportional to the turbulent intensity. The laminar flame speeds, also required by the model, are fuel-specific and are computed using correlations originally developed by Metagalchi and Keck [6–8]. HCCI combustion was modeled using a series of correlations based on experimental and computational studies performed at the University of Michigan [9–10]. These can representively predict auto-ignition, burn-rate, and combustion efficiency of HCCI under a wide range of conditions, including varying pre-combustion temperatures, air-fuel ratios, and residual dilution. In-cylinder heat transfer for both SI and HCCI combustion modes was modeled using the well-known Woschni correlation [12]. A modified version of the classic correlation was employed for the HCCI runs. This Modified Woschni correlation by Chang et al. [13] accounts for the significantly different heat release behavior resulting from HCCI combustion.

Both SI and HCCI engines are knock-limited, so appropriate models capable of reasonably predicting these phenomena had to be included. Knock during SI combustion is due mainly to auto-ignition of the end gas resulting from excessive compression and heating as the flame front progresses. The built-in GT-Power auto-ignition correlation developed by Douaud and Eyzat [14] was used to compute the occurrence of knock in the SI engine. HCCI knock or ringing fundamentally differs from its SI counterpart. The rapid heat release during HCCI combustion causes high pressure-rise rates, which produce large amplitude pressure pulses or acoustic waves within the combustion chamber. After studying these pressure waves in both SI and HCCI engines, Eng [15] derived an expression for the acoustic or ringing intensity, which can then be used to constrain HCCI experiments or simulations.

Because a lot of the improvements in HCCI combustion come from very lean operation, NO\textsubscript{x} emissions, although significantly lower, cannot be handled by a three-way catalytic converter. This requires the actual engine-out emissions to be under the stipulated NO\textsubscript{x} regulation of 1.0 g-NO\textsubscript{x}/kg-fuel. Thus, reasonable estimation of the in-cylinder NO\textsubscript{x} concentration is critical when determining the viable HCCI operating range. For the present study, NO\textsubscript{x} (in the form of NO) is calculated based on the extended Zeldovich mechanism [16].

To minimize complexity and reduce computational time, only the post-throttle intake system was considered, and the desired manifold pressure was directly specified. The exhaust back-pressure was assumed to be engine speed-dependent, and values between 1.01 and 1.1 bar were specified over the operating range between 1000 and 6000 rpm. Engine friction calculations were based on provided friction mean effective pressure (FMEP) data as a function of engine speed. HCCI combustion was enabled through the use of the recompression or negative valve overlap (NVO) strategy, where a large amount of hot burned residuals is trapped and mixed with the incoming fresh charge, resulting in higher pre-compression temperatures that can facilitate the auto-ignition process. The amount of trapped residuals was controlled by symmetrically scaling the full SI valve lifts, while maintaining exhaust valve opening and intake valve closing fixed. Figure 1 shows variation of valve lift and duration, as NVO is increased to achieve HCCI combustion at different load levels.

A comprehensive simulation and parameter matrix was created for the engine operating in both SI and HCCI modes. Table 2 summarizes the main parameters varied for the engine-mapping procedure. The parameter ranges were intended to cover the full operating envelope of each individual engine.

The SI engine was constrained by the occurrence of knock, which was eliminated through the use of a spark-timing optimizer within the simulation. Constraints for the HCCI engine were enforced during post-processing, ensuring that the mapped results were below the imposed Ringing Intensity (R.I), NO\textsubscript{x} emissions (EI-NO\textsubscript{x}) and equivalence ratio (Phi) limits. Results with excessive cycle-to-cycle variability were also discarded. All of the data was imported and post-processed in Matlab [17]. The final engine maps were interpolated along the speed and
load (bmeP) ranges at 250 rpm and 0.25 bar increments, respectively.

Table 2: Engine Simulation and Mapping Matrix

<table>
<thead>
<tr>
<th></th>
<th>SI</th>
<th>HCCI</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fueling</strong></td>
<td>Stoichiometric</td>
<td>5 to 15 mg fuel/cycle 1 mg intervals</td>
</tr>
<tr>
<td><strong>Load/Mixture Control</strong></td>
<td>Intake Pressure 0.3 to 1 bar 0.05-bar intervals</td>
<td>NVO 0 to 220 deg 2-deg intervals</td>
</tr>
<tr>
<td><strong>Engine Speed</strong></td>
<td>1000 to 6000 rpm 500-rpm intervals</td>
<td>1000 to 3500 rpm 500-rpm intervals</td>
</tr>
<tr>
<td><strong>Constraints</strong></td>
<td>Knock Stability</td>
<td>R.I. &lt; 5 MW/m² EI-NOx &lt; 1 g/kg Phi &lt; 1 Stability</td>
</tr>
</tbody>
</table>

2.2. Other Vehicle Assumptions

The simulated vehicles were based on a Model Year (MY) 2010 midsize car. For each parameter (e.g., gearbox, drag coefficient), three values were used, corresponding to three uncertainty cases (referred as “low, medium, and high” cases in the rest of the paper). A total of eight vehicle architectures were modeled: Conventional, Micro HEV (Starter Alternator), Mild HEV (Starter Alternator), Power-Split HEV, Power-Split PHEV 10 and 20 miles, and Series PHEV 30 and 40 miles.

2.2.1. Conventional, Micro, and Mild HEVs

Table 3 summarizes the main assumptions used for the conventional, micro, and mild HEVs. By replacing the regular starter motor found in a conventional vehicle with a more powerful electric machine, the micro HEV allows the engine to shut down instead of idling. In addition to this feature, by using a larger electric machine and higher energy and power battery, the mild HEV can also assist the engine during acceleration by providing a fraction of the requested torque and capturing some of the braking energy.

The engine peak powers for the conventional, micro, and mild HEV vehicles were sized in order to achieve a 0-to-60 mph acceleration in 9 seconds, and sustain a 6% grade at 65 mph at Gross Vehicle Weight (GVW). The results are shown in Figure 2 among the other vehicle configurations (the error bar represents the spread between the different uncertainty cases).

Table 3: Main Assumptions used for Conventional, Micro, and Mild HEVs

<table>
<thead>
<tr>
<th></th>
<th>Conventional</th>
<th>Micro HEV</th>
<th>Mild HEV</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Battery</strong></td>
<td>Lead Acid 12V</td>
<td>Lead Acid 12V</td>
<td>Li-ion 6 Ah 144V</td>
</tr>
<tr>
<td><strong>Electric Machine</strong></td>
<td>N/A</td>
<td>7 kW peak, PM</td>
<td>14 kW peak, PM</td>
</tr>
<tr>
<td><strong>Vehicle Test Mass</strong></td>
<td>1476–1580kg</td>
<td>Same as Conventional</td>
<td>Conventional + 50kg</td>
</tr>
<tr>
<td><strong>Vehicle Controller</strong></td>
<td>N/A</td>
<td>Idle Off</td>
<td>Idle Off Torque Assist Regen. Braking</td>
</tr>
<tr>
<td><strong>Gearbox</strong></td>
<td>5-speed auto. in low and medium cases, 6-speed in high case</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2.2.2. Full HEVs and PHEVs

The full HEV configuration used in this study was a Power-Split architecture, similar to a Toyota Prius or a Ford Escape hybrid, and was equipped with a 6 Ah lithium-ion (Li-ion) battery. For PHEVs, two different electric drive architectures were selected, depending on the All-Electric Range (AER).

- Power-Split technology was chosen for small AER (10 and 20 miles), since this technology shows a high powertrain efficiency in Charge-Sustaining (CS) mode, which will likely be the main operating condition due to the small battery size.
- For higher AER (30 and 40 miles), a series architecture was preferred, to maximize the powertrain efficiency when driving in electric-only mode, which should be the main operating condition. All PHEV batteries were based on the Li-ion Saft VL41M.

The electric machine and the engine powers were sized to achieve 0-to-60 mph acceleration in 9 seconds similarly to the other configurations. In addition, the engine peak power was also sized to sustain the same grade requirement as described in Section 2.2.1 (see Figure 2 for the engine power values). The battery energy and power were sized based on Argonne’s sizing algorithms [18].
HEVs, the battery energy was defined in order to capture the entire regenerative braking energy on the Urban Dynamometer Driving Schedule (UDDS) cycle. For PHEVs, the battery power was sized to follow a specific drive cycle in all-electric mode (UDDS for 10 and 20 miles AER, and US06 [19] for 30 and 40 miles AER). Finally, the PHEV battery energy is such that the vehicles can drive successive UDDS cycles in all-electric mode for their defined AER (see Figure 3 for specific values). Note that the vehicle control used for sizing is different from the one used later for fuel consumption. The vehicle weights for the various configurations are shown in Figure 4.

![Battery Energy for PHEVs](image1)

**Figure 3:** Battery Energy for PHEVs.

![Vehicle Weight after Sizing for all Configurations](image2)

**Figure 4:** Vehicle Weight after Sizing for all Configurations.

### 3. Fuel Savings with Initial Vehicle Control

Using the results from the sizing algorithm, the vehicles were then simulated on the combined drive cycle (UDDS and Highway Fuel Economy Driving Schedule [HWFET]). All fuel consumptions are shown in Liter/100km and are unadjusted under hot conditions. Emissions are not taken into account. For the PHEVs, the fuel consumption values were computed by using the SAE J1711 PHEV procedure. The HEV and PHEV control strategy uses the default algorithm commonly used in PSAT, where the engine operating speed and torque values are chosen based on the maximum power-based efficiency curve. For each vehicle, two simulations were performed with each engine. The fuel consumption ratios are shown in Figure 5.

![Fuel Consumption Ratios for HCCI vs. Regular Engine with Standard Control Strategy](image3)

**Figure 5:** Fuel Consumption Ratios for HCCI vs. Regular Engine with Standard Control Strategy.

The fuel savings of HCCI technology seem to decrease as the vehicles hybridization degree increases. Indeed, while conventional vehicles with an HCCI engine consume 15% less fuel than with a regular engine, series PHEVs achieve only a 2% fuel consumption reduction. One of the reasons for this trend is that the more hybridization, the less the engine runs, and thus, there are fewer opportunities for the HCCI engine to operate at its high efficiency. Among the electric drivetrains, the power-split HEV seems to benefit the most from the HCCI technology, because of longer engine operation time (compared to the PHEV) and the possibility of operating it mainly in the HCCI region.

Table 4 shows the percentage of the time the engine operates in HCCI mode for the different configurations. Because the HCCI technology operates only at low engine torque and at speeds lower than 3000 rpm, it is possible to operate outside this area if the drive cycle requires high engine torque (aggressiveness) or high engine speeds (high-speed highway). For PHEVs, this is particularly true, as low-AER vehicles spend 80% of their time in the HCCI mode and high-AER vehicles spend about 50% of their time in HCCI mode. This is due to the vehicle control strategy, which forces the engine to follow the best power-based efficiency curve, leading to possible non-HCCI operating conditions.

<table>
<thead>
<tr>
<th></th>
<th>UDDS</th>
<th>HWFET</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conv, Micro, Mild</td>
<td>84–87%</td>
<td>81–84%</td>
</tr>
<tr>
<td>Split HEV</td>
<td>91%</td>
<td>96%</td>
</tr>
<tr>
<td>PHEV 10mi</td>
<td>81%</td>
<td>84%</td>
</tr>
<tr>
<td>PHEV 20mi</td>
<td>80%</td>
<td>84%</td>
</tr>
<tr>
<td>PHEV 30mi</td>
<td>52%</td>
<td>52%</td>
</tr>
<tr>
<td>PHEV 40mi</td>
<td>51%</td>
<td>51%</td>
</tr>
</tbody>
</table>

As shown in Figure 6, the maximum efficiency curve first goes through the HCCI region, before moving toward higher torque areas. If the engine power requested by the vehicle controller is higher than the maximum HCCI region power, the engine will operate in high-torque areas, outside of the HCCI region. Consequently, for PHEVs, using this type of control strategy does not take full advantage of the HCCI technology. In the next section, we
will explore changes in the control strategy to optimize engine operating conditions.

However, since the engine is operated at lower power, it is kept on longer (27.4% vs. 22.5% of the time on).

Table 5: Comparison between Default and Modified Control Strategy for a Series PHEV 30 miles AER.

<table>
<thead>
<tr>
<th>UDDS Cycle</th>
<th>Default Strategy</th>
<th>Modified Strategy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine Efficiency</td>
<td>34.1%</td>
<td>38.4%</td>
</tr>
<tr>
<td>Percent Engine ON</td>
<td>22.5%</td>
<td>27.4%</td>
</tr>
<tr>
<td>Percent HCCI Mode</td>
<td>52.9%</td>
<td>98.7%</td>
</tr>
<tr>
<td>Ratio Fuel Consumption</td>
<td>0.99</td>
<td>0.92</td>
</tr>
</tbody>
</table>

4.2. Use of an Atkinson-Cycle Engine for HEVs and PHEVs

Finally, when simulated with the default SI engine, all vehicle configurations (hybrids and non-hybrids) were using an Otto-cycle engine. However, because it is used more frequently in power-split HEVs, an Atkinson-cycle engine could be considered for the baseline PHEVs and HEVs. Because this type of engine offers higher efficiencies, it would not be expected that the fuel consumption reduction produced by the HCCI technology would be as dramatic as shown previously in this paragraph. The Atkinson-cycle engine, which was used in simulation, was based on the Toyota Prius MY2004, and had a peak efficiency of 37.4%. Note that a more recent version of this engine (e.g., Prius MY2010) has a higher peak efficiency and lower fuel consumption. The rest of the baseline vehicles, as well as the HCCI results, remained unchanged.
4.3. Drivability Concerns for HEVs and PHEVs

For HEVs and PHEVs, regular engines are usually operated at low speeds and high torques, as they follow the best power-based efficiency curve. Operating speeds typically range from 1200 to 1600 rpm. On the other hand, as shown in Section 4.1, in order to take advantage of the HCCI high-efficiency area, the hybrid vehicles will operate their HCCI engines in lower-torque and higher-speed regions. Figure 9 shows the operating points (torque and speed values) for an HEV with an Atkinson or an HCCI engine. In the bottom graph (HCCI case), the operating points are mostly located at engine speeds between 2500 and 3000 rpm, which corresponds to the engine peak efficiency region. It is questionable whether or not continuous driving at such engine speeds would lead to drivability issues such as noise, vibration and engine durability, etc. If these operating conditions appear to severely affect drivability, different control strategies should be considered to optimize the trade-off between low fuel consumption and drive quality. In such a case, HCCI technology applied to HEVs and PHEVs could result in reduced fuel savings when compared to regular engines.

5. Impact of Real World Drive Cycles

The previous sections evaluated the impact of an HCCI engine on fuel consumption for various vehicle configurations and scenarios. All simulations were run on the standard UDDS and HWFET drive cycles. In this section, we will analyze the effect of HCCI when the vehicles were run on real world drive cycles, in order to see if the previous fuel saving estimates could be achieved by most drivers during their daily driving.

The real world drive cycles (RWDCs) were recorded by the Environmental Protection Agency (EPA) in Kansas City, in 2005 [20]. More than a hundred drivers’ cars were instrumented to measure their daily driving statistics. All vehicles were model year 2001 and later. For this particular study, only the vehicle speed signals as functions of time were kept to create the drive cycles. One of the 115 drive cycles used in this study (Mercury Mountaineer) is shown in Figure 10.

![Figure 10: Real World Drive Cycle for a Mercury Mountaineer.](image)

Only the conventional and power-split HEV were evaluated for the high uncertainty case. For the baseline default hybrid vehicles, the Atkinson engine is the only one discussed for the comparisons. Figure 11 shows the fuel consumption values as functions of average RWDC vehicle speed for both the regular and the HCCI engines for a conventional powertrain.

![Figure 11: Fuel Consumption Impact of HCCI Technology on RWDC for Conventional Vehicles.](image)

The fuel consumption ratio displayed in Figure 11 varies roughly linearly with the average cycle vehicle speed. Indeed, at vehicle speeds around 25 mph, the HCCI engine fuel savings are around 20%, whereas gains of only 10% can be expected when driving at an average speed higher than 45 mph. As a comparison, the consumption reductions were around 16% for the UDDS and 14% for the HWFET. Thus, it appears that on RWDC, HCCI offers greater fuel savings at low average vehicle speed and worse fuel savings at high average vehicle speed, than when using traditional cycles. At low average cycle speeds, the RWDC tend to have more idling than on the UDDS, leading to more opportunities for the HCCI engine to operate more efficiently than the default engine, and thus, achieve greater fuel savings. On the other hand, at high average cycle speed, the RWDC tend to be more aggressive than the HWFET cycle, resulting in more variation in the vehicle speed. Consequently, the engine torque requested for these cycles is usually higher than the HCCI area, hence, less fuel savings than with the HWFET cycle.
Figure 12 shows the fuel consumption ratio of HCCI compared to a regular Atkinson engine for an HEV simulated on RWDC. As with Figure 11, the points are functions of the average cycle vehicle speed. Contrary to the conventional vehicle, the HCCI fuel savings seem to remain fairly constant, around 17%, for all the different RWDC. This figure is consistent with the HWFET results (17% gains) but is greater than the UDDS (9% gains). Indeed, at low average vehicle speeds, the cycles tend to be more aggressive than the UDDS, causing the engine to turn on more often, and thus, giving the HCCI vehicle the opportunity to operate in higher engine efficiencies than the regular vehicle.

6. Conclusion

In this paper, an HCCI engine efficiency map was developed and implemented in several midsize car powertrain architectures with various degrees of hybridization. The different vehicles, equipped with both HCCI technology and an SI gasoline engine (Otto or Atkinson-cycle), were then simulated on standard and real world drive cycles to estimate the fuel consumption reduction associated with the HCCI technology. The results showed that conventional powertrains would benefit the most from HCCI, especially in mild urban drive cycles. For HEVs and PHEVs, more electric-only driving offers less opportunity for operating the engine in the HCCI area throughout the drive cycle. Consequently, the greater the hybridization, the lower the fuel consumption reduction in HCCI vehicles. Furthermore, when compared to Atkinson-cycle SI engines, the HCCI technology offers more limited fuel consumption reductions for HEVs and PHEVs. Maximizing the engine operating time in the HCCI region for HEVs and PHEVs could lead to potential drivability issues. More research would have to be conducted to determine if different control approaches are needed. Finally, when simulated on real world drive cycles, differences were found in the fuel-saving estimates compared to standard cycles, due mainly to more aggressive and higher vehicle-speed cycles. Nonetheless, the HCCI technology seems to promise moderate to significant fuel consumption reductions for all powertrains considered in this paper, ranging from 6% (for the most hybridized vehicles) to 15% (for conventional powertrains).

7. Acronyms

AER: All-Electric Range  
BMEP: Brake Mean Effective Pressure  
CS: Charge-Sustaining  
EPA: Environmental Protection Agency  
FMEP: Friction Mean Effective Pressure  
GVW: Gross Vehicle Weight  
HCCI: Homogeneous Charge Compression Ignition  
HEV: Hybrid Electric Vehicle  
HWFET: Highway Fuel Economy Driving Schedule  
Li-ion: Lithium-ion  
MY: Model Year  
NVO: Negative Value Overlap  
PHEV: Plug-in Hybrid Electric Vehicle  
PM: Permanent Magnet  
PSAT: Powertrain Systems Analysis Toolkit  
RWDC: Real World Drive Cycle  
SI: Spark-Ignited  
UDDS: Urban Dynamometer Driving Schedule

8. References


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