Evaluation of Ethanol Blends for Plug-In Hybrid Vehicles Using Engine in the Loop

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ABSTRACT

Their easy availability, lower well-to-wheel emissions, and relative ease of use with existing engine technologies have made ethanol and ethanol-gasoline blends a viable alternative to gasoline for use in spark-ignition (SI) engines. The lower energy density of ethanol and ethanol-gasoline blends, however, results in higher volumetric fuel consumption compared with gasoline. Also, the higher latent heat of vaporization can result in cold-start issues with higher-level ethanol blends. On the other hand, a higher octane number, which indicates resistance to knock and potentially enables more optimal combustion phasing, results in better engine efficiency, especially at higher loads.

This paper compares the fuel consumption and emissions of two ethanol blends (E50 and E85) with those for gasoline when used in conventional (non-hybrid) and power-split-type plug-in hybrid electric vehicles (PHEVs). Engine-in-the-loop (EIL) test results from a previous study of an E85-series PHEV show about 4% lower fuel energy consumption than gasoline because of better engine efficiency at high loads. In a conventional vehicle, the decrease in fuel energy consumption when gasoline is compared with E85 is less than 1%.

The series PHEV operates as an electric vehicle when in charge-depleting (CD) mode. For the power-split PHEV, the CD mode of operation has multiple, but infrequent, “engine on” events, resulting in different engine utilization than the series PHEV. Differences in the hybridization configuration also result in different regions of operation for the engine in the CD, as well as the charge-sustaining (CS), mode of operation. The vehicle control strategy for a particular configuration remains the same for the different fuel blends.

For the power-split PHEV, we assess the sensitivity of fuel consumption and emissions to the three fuels using EIL testing and compare them with EIL results for a series PHEV and a conventional vehicle. We propose changes to the PHEV control strategy to optimize the vehicle system for each fuel blend and configuration.

INTRODUCTION

Ethanol and ethanol-gasoline blends are being considered as an alternative to gasoline for spark-ignition (SI) engines. These blends have some disadvantages when compared with gasoline. The lower energy density of the fuel mix results in higher volumetric fuel consumption, which decreases the vehicle range per tank of fuel. The higher latent heat of vaporization results in cold-start issues [1]. The issues are more pronounced when higher-level ethanol blends are used. On the other hand, higher knock resistance results in better engine efficiency at higher loads [2]. Table 1 compares the relevant fuel properties of ethanol gasoline blends to those of gasoline. The table also lists the engine- and vehicle-level impacts of the fuel properties.

Plug-in hybrid electric vehicle (PHEV) technology, which is currently being introduced into the transportation market [3,4], can reduce petroleum consumption through the use of large, rechargeable lithium (Li)-ion batteries and overnight charging from the grid. While multiple powertrain configurations — each with a different energy flow path between the engine, the battery, and the wheels — are possible for PHEVs, the series-type PHEV (series configuration) and power-split PHEV (power-split configuration) are the two most commonly addressed in the literature [5,6]. Although the engine utilization varies with the variation in the powertrain configuration of a hybrid, it is well understood that fuel economy gains are attributable to (1) engine operation at higher loads (and therefore better efficiency) than a conventional, non-hybrid vehicle, and (2) the regenerative braking that is possible with batteries [7].
Table 1 – Ethanol and gasoline blend properties and their engine and vehicle impacts

<table>
<thead>
<tr>
<th>Fuel properties of ethanol gasoline blends (compared with gasoline)</th>
<th>Engine-level impact</th>
<th>Vehicle-level impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower energy density</td>
<td>Higher volumetric fuel flow for the same shaft power</td>
<td>Greater fuel consumption</td>
</tr>
<tr>
<td>Higher latent heat of vaporization</td>
<td>Unreliable cold start for higher blend ratios.</td>
<td>Higher emissions as a result of failed combustion; issue might be aggravated for blended-mode PHEV operation.</td>
</tr>
<tr>
<td>Better knock properties</td>
<td>More efficient high-load operation</td>
<td>Lower fuel consumption at high loads can be advantageous for hybrid operation</td>
</tr>
</tbody>
</table>

The flex-fuel vehicles that are currently available in the market have demonstrated improvements in terms of material compatibility, calibration changes to meet fueling requirements, and injection timing. The higher octane number of ethanol blends can be further exploited by using higher compression ratios and making additional calibration changes [8, 9]. While the negative impact of ethanol-gasoline blends’ lower energy density in conventional vehicles has been documented [2, 10, 11], this paper examines the combined impact of lower energy density (negative) and better engine efficiency (positive) using a 2.2-L spark-ignition direct-injection (SIDI) engine in a PHEV. As stated earlier, because the engine operates at higher loads in a PHEV, the efficiency gains offered by ethanol-gasoline blends, compared with gasoline alone, are more pronounced.

The engine used in this study has an electronic control unit (ECU) that is fully accessible for calibration. The parameter changes to the ECU for the different fuels, for this experiment, are restricted to fuel injection duration to maintain stoichiometric combustion for the different blends. The ECU uses a knock detection sensor to retard spark timing on each cylinder individually in case of engine knock. Higher-compression-ratio engines would demonstrate additional efficiency gains with ethanol blends, but such changes are not a part of this experiment.

In a previous study performed at Argonne National Laboratory, researchers compared the increase in fuel consumption attributable to ethanol blends for a conventional vehicle (baseline) and a series PHEV [12]. The study revealed that that the fuel consumption penalty for E85 is lower for the series PHEV than for the conventional vehicle because of the greater engine efficiency of E85 in the hybrid case. The series PHEV was operated as an electric vehicle in the charge-depleting (CD) mode. Therefore, the decrease in the fuel consumption penalty was for the charge-sustaining (CS) mode of vehicle operation. This paper compares the fuel consumption penalty for E50 and E85 in the same conventional vehicle (baseline) versus a power-split PHEV vehicle. The difference in the configuration of the hybrid vehicle (power-split versus series PHEV) results in a different number of “engine on” events during the drive cycle and different engine utilization, as well.

The following sections describe the design of the experiment and the engine-in-the-loop (EIL) setup and provide details about the sizing and operation of the power-split vehicle used for this study.

**ENGINE IN THE LOOP SETUP**

Figure 1 shows the block diagram for the EIL setup at Argonne. The power-split PHEV simulation model was developed in AUTONOMIE [13] and runs in real time on a dSPACE system. Throttle and dynamometer speed commands are sent to the engine throttle body and the dynamometer through the dynamometer controller. Engine torque is measured by the HBM torque sensor on the engine shaft, and the torque feedback is used to propel the virtual vehicle in AUTONOMIE.
The 2.2-L Ecotec Opel SIDI engine has a stock, close-coupled, three-way catalyst (TWC) on the exhaust line. Emissions are sampled post catalyst and are analyzed by using a Horiba MEXA Model 7100D exhaust gas recirculation (EGR) emissions analyzer. Total hydrocarbons (THC), nitrogen oxides (NO\textsubscript{x}), and carbon monoxide (CO), measured as volumetric concentrations, are converted to emissions (in g/mi) by using the measured air and fuel flow to the engine. The engine coolant loop is set up to replicate an “in-vehicle” coolant loop, with a constant-speed fan blowing across the radiator, similar to the setup for chassis dynamometer vehicle tests. Thus, the cold-start behavior of the engine is similar to the behavior of an in-vehicle cold-engine start [1]. Figure 2 is a picture of the actual engine: the dynamometer setup with the coolant system, the TWC, and the HBM speed-torque sensor. For a blended-mode power-split PHEV, a separate vehicle control strategy is implemented for cold-start conditions, with a focus on limiting cold-start emissions. The control strategy when the engine is “hot” is focused on maximizing fuel economy. As mentioned, with the blended-mode operation, multiple cold-start events are possible. Therefore, catalyst bed temperature is used as a feedback to detect cold-start conditions and also to transition to the default, ‘hot’ vehicle control.

**DESIGN OF EXPERIMENT**

The main objective of this study is to evaluate whether the improved engine efficiency at high engine loads (observed in hybrid operation) reduces the energy density impact of ethanol-gasoline blends. The improved efficiency impact is assessed by comparing the energy density impact of the ethanol-gasoline blends on the power-split PHEV to the energy density impact on a conventional vehicle. Figure 3 is a matrix showing the experiment design. The power-split PHEV is subjected to six consecutive UDDS (urban dynamometer driving schedule) cycles, with 10 minutes soak time in between each cycle. The baseline conventional fuel economy for
each fuel is measured on a single, cold-start UDDS cycle. The fuel consumption for the blended-mode PHEV is calculated using city-specific, multi-day, individual utility factor (UF) [14], while the conventional fuel consumption is the unadjusted value for the cycle.

![Figure 3 – Design of experiment matrix](image)

Because this is a study evaluating the impact of different levels of ethanol blends, the same vehicle control strategy is maintained for the three fuels, resulting in identical battery and engine (shaft) power throughout the drive schedule for the three fuels. To provide a fair comparison between fuels, stoichiometric operation is ensured for the three fuel blends by adjusting the fuel injection duration for each combustion event (as a function of speed and load) for each blend ratio.

**POWER-SPLIT PHEV SPECIFICATIONS AND OPERATION IN BLENDED MODE**

**PHEV SPECIFICATIONS**

Table 2 lists the design requirements for the power-split PHEV, and Table 3 lists the specifications for the power-split PHEV and the baseline conventional vehicle to meet the requirements for this study. The components of the power-split PHEV were sized using the automated sizing routine in AUTONOMIE [13] to meet the requirements specified in Table 2. Because this is an EIL experiment (i.e., real engine in a virtual vehicle), the 2.2-L engine was used for the study although the sizing algorithm might have suggested otherwise.

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Power-split PHEV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acceleration: 0-60 mph</td>
<td>~ 9 seconds</td>
</tr>
<tr>
<td>Max vehicle speed</td>
<td>More than 100 mph</td>
</tr>
<tr>
<td>Grade</td>
<td>6% grade at 55 mph</td>
</tr>
<tr>
<td>Equivalent electrical range</td>
<td>~ 20 miles</td>
</tr>
</tbody>
</table>

Table 3 – Power-split PHEV and baseline conventional vehicle component specifications

<table>
<thead>
<tr>
<th>Component</th>
<th>Power-split PHEV</th>
<th>Conventional</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gross vehicle weight (kg)</td>
<td>1,859</td>
<td>1,758</td>
</tr>
<tr>
<td>Engine power (kW) (2.2-L SIDI engine)</td>
<td>110</td>
<td>110</td>
</tr>
</tbody>
</table>

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PHEV OPERATION

As stated earlier, the PHEV operates in blended-mode operation. Figure 4 illustrates the vehicle operation. The figure shows battery state of charge (SOC), engine speed (in radians per second), and vehicle speed (scaled). The battery SOC is allowed to deplete to 30% (from an initial SOC of 90%), beyond which the battery maintains its SOC (CS operation). In the blended mode, the vehicle control strategy turns the engine on whenever the vehicle speed is greater than 20 mph or the power demand at the engine is greater than 32 kW. The first “engine on” event is a cold start, and therefore the vehicle control strategy utilizes the engine in a controlled fashion to limit emissions.

![Figure 4 – Power-split PHEV operation over consecutive UDDS cycles](image)

RESULTS AND ANALYSIS

EFFICIENCY GAIN FOR E50 AND E85 AT HIGH ENGINE LOAD

Figures 5 (a) and 5(b) show the ‘efficiency gain’ map for E50 and E85, compared with gasoline (E0)). This is a map of the absolute difference between the ethanol blend and gasoline efficiency, so if the E85 efficiency is say 35% and the gasoline efficiency is 33%, for the same speed and load point, then the efficiency difference map between E85 and E50, for that speed and load, would show 2%. This map was generated from steady-state tests of the 2.2-L SIDI engine that is used for the EIL tests. The islands of improved efficiency at high loads can be clearly seen for both the fuels. The efficiency gain maps also show the peak and minimum torque curves for the engine. Efficiency gain contours beyond the peak torque curves are present because of the limitations of the plotting tool; they do not signify engine operation beyond the peak torque curve for either of the fuels.
POWER-SPLIT PHEV OPERATION WITH ‘NORMAL’ ENGINE LOAD

Figure 6 shows the fuel consumption for the conventional vehicle (cold start and hot start) and the power-split PHEV (UF weighted). As the figure shows, the fuel consumption increases with the increase in the ethanol content of the fuel blend. Table 4 shows the percentage increase in fuel consumption compared with gasoline for the conventional vehicle (hot start) and the power-split PHEV. The increase in fuel consumption for the conventional vehicle and the power-split PHEV is similar for a given ethanol blend.
The increase in fuel consumption for both vehicle types is comparable to the difference in energy density between E50 and gasoline, and E85 and gasoline, respectively. As the results in Table 4 indicate, the anticipated impact of increased engine efficiency for the ethanol blends in the PHEV case is not observed. This is because, although the engine operates at high load for the blended-mode PHEV, it does not operate in the ‘efficiency gain’ region for E50 or E85.

Figure 7 shows the engine operating points and the efficiency gain map for E85. The figure shows that there are minimal excursions in the efficiency gain regions for power-split PHEV operation. The test-to-test variation in the fuel consumption results using the current EIL setup is about +/-1%. The engine usage in the efficiency gain region is not high enough to reflect the impact of improved engine efficiency at high loads. As stated earlier, a previous study involving series PHEV operation [12] revealed that the energy density penalty for E50 and E85 is reduced for series PHEV operation compared with conventional vehicle operation.

Figure 8 shows the engine operating points for the series PHEV on the E85 ‘efficiency gain’ map. The transient nature of the engine operation results in the torque sensor measuring inertia effects in addition to engine torque, and therefore the engine speed –torque points cross the maximum torque curve, momentarily. Table 5 compares the fuel consumption increase for the conventional vehicle (hot start), the series PHEV, and the power-split PHEV. The data indicate that the fuel consumption penalty is lower for the series PHEV, reflecting gains attributable to higher engine efficiency for the ethanol blends. Comparison of the engine operation for the series PHEV (Figure 8) and the power-split PHEV (Figure 7) shows that the engine operates at higher loads for the series PHEV than for the power-split PHEV. As shown in Table 5, sufficient engine operation in the efficiency gain region of E85 results in increased engine efficiency for E85 and a lower energy density penalty. While the fuel consumption for the power-split PHEV is UF-weighted over consecutive UDDS cycles, the series PHEV fuel consumption is only for CS UDDS operation. Engine load is higher for CS operation compared with CD operation because, for CS operation, the engine is supplying road load power, as well as providing power to maintain battery SOC. In addition, the series PHEV has a higher mass, which results in increased engine load when the engine is on. As stated earlier, the series PHEV operates as an electric vehicle in the CD mode.
Figure 7 – Efficiency gain regions for E85 (compared with gasoline) and power-split PHEV regions of operation.

Figure 8 – Engine operation for a series PHEV [12].

Table 5 – Fuel consumption increase compared with gasoline for a conventional vehicle (hot start), series PHEV, and power-split PHEV

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Conventional vehicle (hot start) (%)</th>
<th>Series PHEV (CS mode) (%)</th>
<th>Power-split PHEV (UF weighted) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>E50</td>
<td>18.4</td>
<td>15</td>
<td>18</td>
</tr>
<tr>
<td>E85</td>
<td>27</td>
<td>25</td>
<td>28</td>
</tr>
</tbody>
</table>
POWER-SPLIT PHEV OPERATION WITH INCREASED ENGINE LOAD

The vehicle control strategy sets the default engine torque demand to operate the engine at the highest possible efficiency (for gasoline) and provide road load and battery power. In hybrid or plug-in hybrid operation, it is possible to independently set engine load because engine load and road load demand are de-coupled by the battery. To take advantage of the improved engine efficiency at higher loads with ethanol blends, the engine load for the power-split PHEV was increased by increasing the engine torque demand when the engine is on. Figure 9 shows the engine operating points with the normal engine loads for the power-split PHEV (similar to Figure 7) and increased engine load. Increase in engine torque demand when engine is on results in lower battery usage.

![Figure 9 – Power-split PHEV engine operation with increased engine load](image)

Table 6 compares the fuel consumption increase for E50 and E85 (compared with gasoline) for the conventional vehicle (hot start), series PHEV, power-split PHEV with normal engine load and for the power-split PHEV with increased engine load. The table shows that with increased engine load, the energy density penalty for E50 and E85 is reduced, similar to the series PHEV case.

Table 6 – Fuel consumption increase compared with gasoline for a conventional vehicle (hot start), series PHEV, and power-split PHEV

<table>
<thead>
<tr>
<th>Ethanol blend</th>
<th>Conventional vehicle (hot start) (%)</th>
<th>Series PHEV (CS mode) (%)</th>
<th>Power-split PHEV (UF weighted) (%)</th>
<th>Power-split PHEV (increased engine load, UF weighted) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>E50</td>
<td>18.4</td>
<td>15</td>
<td>18</td>
<td>14.3</td>
</tr>
<tr>
<td>E85</td>
<td>27</td>
<td>25</td>
<td>28</td>
<td>25.8</td>
</tr>
</tbody>
</table>

Figure 10 shows instantaneous engine efficiency for gasoline and E85 on the second hill of the UDDS cycle for normal engine loads and increased engine loads. The vehicle speed (with scaling and offset) is also shown in the figure. The figure shows that, at normal engine loads, the engine efficiency is the same for gasoline and E85. At increased engine loads, E85 efficiency increases, relative to gasoline, because of lower throttling losses. With gasoline, the ECU retards the spark timing to prevent knock, resulting in a net decrease in engine efficiency. This difference in engine efficiency for gasoline and E85 at high torque is reflected in the results in Table 6. The UDDS cycle used for this study is generally considered a less aggressive cycle compared with real world driving [15]. If the experiment is repeated over a more aggressive driving cycle, the energy density impact of E50 and E85 would be further reduced.
Figure 10 – Engine efficiency for normal and increased engine load — gasoline and E85, for the second hill of the UDDS cycle

Table 7 shows the fuel and electrical consumption for the power-split PHEV and power-split PHEV with increased engine load, for gasoline, E50, and E85. Although the energy density penalty decreases with increased engine loading, overall fuel consumption, for any fuel, increases with a commensurate decrease in electrical consumption. As stated, the electrical and fuel consumption calculations are UF based.

Table 7 – Fuel and electrical consumption for power-split PHEV and power-split PHEV with increased engine load

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Power-split PHEV</th>
<th>Power-split PHEV with increased engine load</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Electrical</td>
<td>Fuel consumption (L/100 km)</td>
</tr>
<tr>
<td></td>
<td>consumption</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(Wh/mi)</td>
<td></td>
</tr>
<tr>
<td>Gasoline</td>
<td>111.3</td>
<td>3.26</td>
</tr>
<tr>
<td>E50</td>
<td>111.6</td>
<td>3.98</td>
</tr>
<tr>
<td>E85</td>
<td>111.3</td>
<td>4.58</td>
</tr>
</tbody>
</table>

Table 7 indicates a net increase in fuel consumption (and a commensurate decrease in electrical consumption) with increased engine loading. Although increasing the engine load provides more efficient engine operation, a miles per gallon gasoline equivalent (MPGGe) [16] result might still favor the normal load case over the blended mode for any given fuel because of the greater amount of electric operation (higher Wh/mi).

EMISSIONS COMPARISON BETWEEN NORMAL AND INCREASED ENGINE LOAD

As stated, stoichiometric operation of the engine is ensured for the three fuels by changing the duration of fuel injection based on the ethanol content of the blend. Also, a three way catalyst is installed in the exhaust line and emissions are measured post catalyst. Therefore, the impact of ethanol blends on emissions cannot be seen, and the emissions are comparable across the three fuel blends for a particular vehicle configuration and control. Therefore, emission results for the three different fuels are not presented.

Figure 11 shows the NOx emissions for normal engine load and increased engine load during the first five consecutive UDDS cycles for the power-split PHEV. The first UDDS cycle is a cold start; therefore, the energy management strategy limits engine usage to reduce cold-start emissions so the NOx values for the second UDDS cycle are higher than those for the first UDDS cycle. Because the
fifth UDDS cycle is in CS operation, the engine operates at higher loads compared with the first four cycles, resulting in higher NO\textsubscript{x} emissions than in the third and fourth UDDS cycles. In general, NO\textsubscript{x} emissions are higher for the increased load case.

![Figure 11](image1.png)

*Figure 11 – NO\textsubscript{x} emissions for power-split PHEV — normal and increased engine load*

Figure 12 shows the THC emissions for the normal engine load and the increased engine load. Similar to the NO\textsubscript{x} case, THC emissions are higher with increased engine load. THC is highest for the first, cold-start UDDS cycle.

![Figure 12](image2.png)

*Figure 12 – THC emissions for power-split PHEV — normal and increased engine load*
VEHICLE SYSTEM OPTIMIZATION APPROACH

In the previous section, we described how, in order to exploit the increased efficiency at high loads, engine torque demand was increased. Figure 13 shows the engine operating points for the increased engine load case for the power-split PHEV. As indicated by the arrow, there is a potential to further reduce the energy density penalty of the ethanol blends by operating the engine at higher speeds.

The correct approach to determining the most suitable area of operation of the engine is to consider the system efficiency, using modeling and simulation.

![Figure 13 – Change in engine operation could result in further fuel economy improvements for E85](image)

1. The vehicle generator (which is used to control engine speed) and traction motor should be resized in order to make the engine work closer to the best efficiency island.
2. The engine efficiency map, the generator map and the motor map should be considered together to evaluate system efficiency.
3. Apart from heuristic control, optimization techniques [19], [20], [21] should be considered to identify vehicle control strategy parameters which would maximize the fuel economy with the ethanol – gasoline blends.
4. A model based design approach [22], which involves a simulation study with engine in the loop validation, would ensure that while fuel economy is being maximized, emissions are within pre-decided constraints should be used.

SUMMARY AND CONCLUSION

The authors leveraged several existing capabilities at Argonne National Laboratory — vehicle systems modeling in AUTONOMIE, expertise in flex-fuel engine and emissions research, and EIL capability — to compare the fuel consumption of a power-split PHEV for ethanol gasoline blends: E0 (gasoline), E50, and E85. Such a comparison is possible by ensuring identical vehicle operation (engine utilization) and stoichiometric combustion for the three fuels. For conventional vehicles, the lower energy density of the ethanol-gasoline blends results in increasing fuel consumption as the quantity of ethanol in the blend increases. With hybrid operation, there is a potential to reduce the energy density impact by exploiting the higher efficiency of these engines at high loads, due to better knock properties. A previous study with a series PHEV demonstrated the impact of the higher efficiency of ethanol blends. For the series PHEV, the engine turns on only in the CS mode, providing road load demand and charging the battery at the same time. This generates sufficient engine load to take advantage of the efficiency improvements associated with ethanol blends at high engine loads.

In the CD (blended) mode operation in the power-split PHEV, the engine only provides road load demand. We observed that this mode of operation does not load the engine sufficiently to take advantage of the better engine efficiency of the ethanol blends.
Therefore, the vehicle control strategy was modified to increase the engine load (and reduce battery usage). The energy density penalty of the ethanol-gasoline blends is reduced for the power-split PHEV with increased engine load (compared with a conventional vehicle). There is a slight increase in emissions with the increase in engine load.

There is further potential to reduce the energy density penalty of the ethanol-gasoline blends through vehicle system optimization, while maintaining emissions within limits.

**FUTURE WORK**

An important aspect of the use of flex fuels in engines is their cost at the pump and overall life-cycle cost compared with gasoline. The fuel consumption results from the tests and simulation could be used to perform a net present value (NPV) analysis of operating cost [17] and a life-cycle analysis using Argonne’s life-cycle analysis toolkit — GREET [18].

This study focuses on fuel economy improvement for one driving trip. With NPV analysis, the focus is on choosing a vehicle control strategy to minimize vehicle operating cost over the life of a vehicle. For PHEVs, an important aspect to overall operating cost savings is battery life. Therefore, a comprehensive study, which looks at maximizing the fuel economy for the ethanol blends through vehicle system optimization, while considering NPV minimization (of operating cost) and battery life, is possible.

**REFERENCES**

23.

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