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Assessment of Fuel Consumption of a co-Optimized Gasoline Compression Ignition Engine in a Hybrid Electric Vehicle Platform

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Abstract

Increasing regulatory demand to reduce CO_2 emissions has led to an industry focus on electrified vehicles while limiting the development of conventional internal combustion engine (ICE) and hybrid powertrains. Hybrid electric vehicle (HEV) powertrains rely on conventional SI mode IC engines that are optimized for a narrow operating range. Advanced combustion strategies such as Gasoline Compression Ignition (GCI) have been demonstrated by several others including the authors to improve brake thermal efficiency compared to both gasoline SI and Diesel CI modes. Soot and NO_x emissions are also reduced significantly by using gasoline instead of diesel in GCI engines due to differences in composition, fuel properties, and reactivity. In this work, an HEV system was proposed utilizing a multi-mode GCI based ICE combined with a HEV components (e-motor, battery, and invertor).

To determine the total fuel consumption over the FTP75 drive cycle, a fueling map from a multi-mode GCI combustion presented in a previous study was used as the input data set for the 1D HEV drive cycle model (GT Drive) of a mid-sized SUV. An HEV operation strategy was proposed and followed by parametric studies of components including the e-motor sizing (20 kW to 80kW) and the battery capacity (2Ah to 8Ah), and evaluation on their impacts on fuel consumption.

Introduction

Gasoline compression ignition (GCI) has been demonstrated to have the potential to meet future CO_2 regulations and emissions while having the advantage of using existing refineries infrastructures and subsequent economies of scale for a robust energy supply [1, 2, 3, 4]. Hybrid powertrains have traditionally only been produced with conventional SI IC engine technologies. In this work, a Multi-mode GCI engine will be co-optimized with a P2 Hybrid system for both battery size and motor generator unit (MGU) power size.

Background on GCI Research

Global regulatory demands for a cleaner environment have led automakers and research institutions to focus on developing new lean burn combustion concepts to reduce engine-out emissions while at the same time improving thermal efficiency. Some of the advanced engine combustion concepts under active development are homogeneous charge compression ignition (HCCI), and gasoline compression ignition. The GCI combustion mode includes both partially premixed compression ignition (PPCI) and mixing-controlled compression ignition (MCCI), characterized by one-stage heat release as typical gasoline spark ignited combustion and two-stage heat release as typical diesel compression ignited combustion, respectively [1, 2, 3]. GCI combustion mode can result in better than diesel thermal efficiency and soot emissions for the same engine out NO_x level as shown in our previous work [1]. This was found to be a result of the extended ignition delay of gasoline RON 91 E10 fuel versus #2 ULSD diesel fuel [5], furthermore, as a result of the decreased fuel pressure requirement which reduced pump work and parasitic losses. Further development of GCI combustion modes under lean conditions with copious levels of exhaust gas recirculation (EGR) and intake boost with high compression ratios (CR) would enable even further improved brake thermal efficiency (BTE) and decrease NO_x and soot emissions. Additionally, the less processed light fuels with lower RON as naphtha compared to current gasoline fuels can be used and actually preferred in the GCI engines, reducing the fuel processing cost [6, 7].

In HCCI combustion mode, fuel is injected very early in the compression stroke, in which the air-fuel charge undergoes a homogeneous mixing prior to autoignition. This combustion mode can guarantee a significant reduction in NO_x and lower soot emissions since the air-fuel charge is fully premixed. However, HCCI combustion is controlled by the chemical kinetics of the mixture and therefore, controlling the HCCI combustion phasing proves to be difficult and results in a narrow operating range [8]. On the other hand, in GCI combustion mode, the fuel is injected later during the compression stroke with multiple injections to avoid fully premixing and improve combustion phasing control while reducing NO_x and smoke. Generally, as part of the GCI combustion mode strategies, in PPCI, less amount of fuel stratification and lower injection and boost pressures are applied, whereas in MCCI, a later injection timing for the pilot is applied in conjunction with higher boost pressures [1]. Therefore, GCI can still achieve some of the benefits of HCCI, like reduced NO_x and smoke but with reductions in pressure rise rates and improved combustion phasing control.

One of the other advanced engine combustion concepts is the spark assisted compression ignition (SACI). In this concept, the air-fuel charge is homogenous similar to that in the HCCI concept. On the other hand, SACI implements a spark ignition to initiate the flame, which elevates the temperature and pressure of the remaining homogeneous mixture. As a result, most of the charge will simultaneously auto-ignite [9,10]. Therefore, the spark is used in SACI over the entire engine operating map to control the combustion phasing unlike in HCCI.

Mazda's spark-controlled compression ignition (SPCCI) mode which is developed for their SkyActive-X production engine, uses a spark to assist fuel-air mixture autoignition over the most of the engine operating map [12]. For higher loads, higher engine speeds, and cold start, the engine will switch to SI mode only. In comparison to SACI, the SPCCI mode employs a relatively homogeneous and dilute air-fuel charge, in addition to controlling the combustion phasing based on the spark ignition. Diluting the air-fuel charge is applied by having an ultra-lean conditions or exhaust gas recirculation (EGR). This technology will pave the way for the other abovementioned technologies to potentially to go into production also.

For GCI to go into production a few challenges need to be resolved to operate the engine over the entire speed and load range. These challenges were mentioned in Zyada & Zoldak et al. [1]. At low loads, the combustion is unstable due to the low reactivity of gasoline. Charge air heating in addition to increasing boost pressure is used for such conditions. Delphi employed an exhaust rebreathing strategy in a four-cylinder engine to attain low load operation [4]. At high loads, maintaining combustion noise within specifications increases the challenge to control the pressure rise rates [1, 5]. The authors proposed in previous work a multi-mode engine that has the GCI mode running through the entire engine speed range at medium to high load range. For low loads, the engine could be started by using a spark ignition mode [1]. One other innovative technique to further optimizing the operating range for the proposed multi-mode engine in [1], and bringing it to the market faster, is by combining it with a hybrid system. This is true especially with the new upcoming strict standards to ban new ICE-only passenger vehicles in regions of the world.

Background on HEV Powertrain

Hybrid electric vehicles (HEV) have focused their development on the electrical components of the battery, e-motor, invertor and control strategies whilst utilizing conventional spark ignited base engines, which have been being advanced. Our previous work showed GCI engine has the potential of significant reductions in both fuel consumption and emissions over SIDI (spark ignited direct injection) engines [1]. In this work, the team has conducted studies investigating GCI mode operation and co-optimizing it with an HEV platform by studying the effect on total cycle fuel consumption. Strategies that are employed include EV only mode, regen mode, as well as combined mode HEV which consists of both GCI and EV added together.

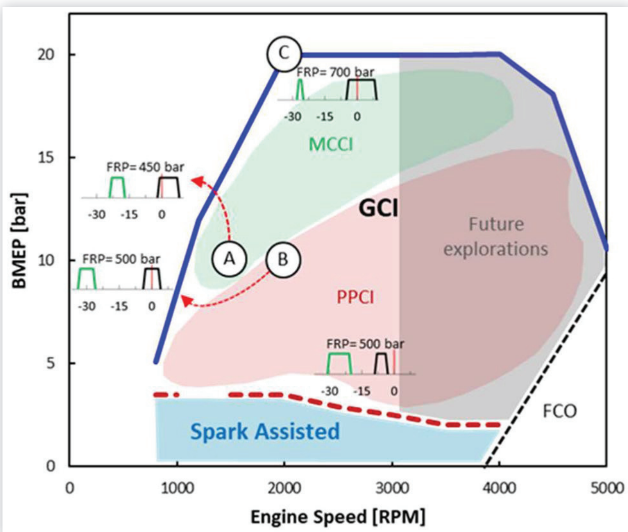
Researchers have shown that hybridization can successfully optimize the fuel consumption of an IC engine while reducing emissions. Melaika et al. compared the influence of four different 48 V powertrain architectures on CO_2 emissions [13]. There are five common hybrid architectures: P0, P1, P2, P3 and P4. P0 system has the electric machine (EM) mechanically linked to the ICE at the front end through a belt, while P1 system has the EM directly connected to the crankshaft of the ICE. The EM is decoupled from the ICE and integrated to the input of the transmission in a P2 system, or connected through a gear mesh at the output of the transmission in a P3 system, while positioned on the rear differential in P4 system [14]. For the four architectures, P0, P1, P2, and P3, studied in their simulation using the GT-Suite, Melaika et al. predicted 9, 10, 25, and 26% CO_2 reduction respectively. Compared to a non-hybrid baseline, CO_2 was reduced from 130 g/km to 98 g/km CO_2 over the WLTC cycle. This is close to the 2020 target of 95 g/km [15]. The P2 and P3 architectures achieved significantly better fuel efficiency, even with lower electric motor power level compared to a conventional powertrain with a start-stop system by 19% on average.

Zaneli et al. performed a simulation study of P1-P3 48 V hybrid powertrain architectures that contain different engine technologies in a C-segment vehicle [16]. They focused on the benefits of reducing CO_2 emissions and on the cost of the technology associated with the amount of CO_2 reduction. For this purpose, they applied hybridization to both SI port fuel injection naturally aspirated (NA) engine and to a turbo SIDI engine. Their results showed that CO_2 was reduced between 12.4% and 15.6% for the P3 architecture for the turbo SIDI engine, versus only 1% improvement for the NA engine combined with the P3 architecture. Combining both engines with P1 and P2 hybrid architectures showed an increase in both CO_2 emission and the powertrain cost for the NA engine comparing with the turbo engine. Zaneli et al. concluded that development new engine technologies are still beneficial to be combined in a hybrid powertrain despite a worldwide trend for fully electric vehicles. Finally, Conway et al. demonstrated the power of hybridizing the ICE by implementing turbocharger sizing, compression ratio, and enrichment mitigation for a 48 V hybrid system in P0, P1 or P2 configurations combined with 1L (1 liter displacement) and 2L engines [17]. Their GT-Drive simulations showed that 15kW battery power to the crankshaft enables an increase in the compression ratio from a baseline CR of 10:1 to 13:1 with a hybrid 1L engine and to 11.3:1 with a hybrid 2L engine because the engine can be operated at lower load in Hybrid mode thus avoiding engine knock. The power of 15 kW enables downsizing the turbocharger resulting in 18% improvement in BSFC for the 2L hybrid engine at 6000 rpm. Some examples of hybrid vehicles are listed in Table 1.

TABLE 1 Current hybrid production vehicles

Manufacturer	Toyota	Toyota	Honda
Model	Prius	Camry	Insight
Year	2021	2021	2019
E-Motor Power (kW)	53	88	96
Battery Capacity (Ah)	6.5	6.2	4.4

FIGURE 1 Multi-mode GCI operating map.



Charge dilution by means of EGR has been used by several researchers in SI mode engines to mitigate knock especially under boosted conditions and enable more advanced combustion phasing in combination with hybrid powertrains to improve the overall fuel economy of a vehicle [18,19].

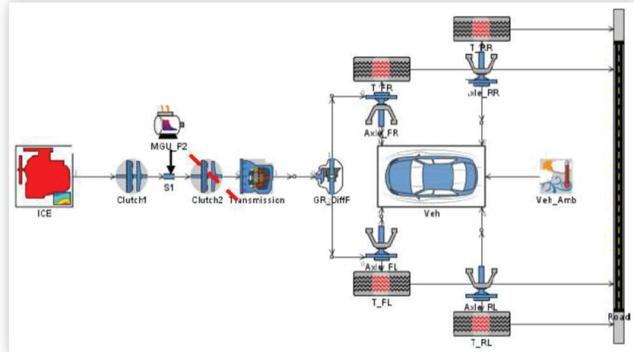
Motivation

In this study, a Hyundai 2.2L 4-cylinder engine and has been tested using RON 91 E10 gasoline in multi-mode GCI mode as shown in Figure 1. The multimode GCI combustion system is capable of operating the engine in distinct high efficiency GCI modes including Mode (A) MCCI strategy, Mode (B) PPCI strategy or Mode (C) which is a late DI MCCI strategy. The multimode GCI combustion system is used as the input for the P2 hybrid powertrain model and a simulation was conducted to understand their combined potential benefits. The objective was to assess the potential of the overall powertrain efficiency and provide directional guidance to better determine the appropriate MGU and battery sizing to take advantage of the multimode GCI operation mode to improve overall vehicle fuel consumption and emissions.

Overall Model Setup

GT-SUITE, a model-based systems engineering CAE simulation software developed by Gamma Technologies, is widely used to analyze vehicle system-level fuel economy

FIGURE 2 Vehicle model setup of P2 hybrid with multi-mode GCI engine.



performance and hybrid vehicle design optimization [20,21], and also employed in this study. The overall GT-Drive model setup is presented in Figure 2 and the following section provide details about the engine, the vehicle, the transmission, tires and road load as well as the battery and MGU hybrid system and controls.

ICE Model Setup

The model utilized an ICE featuring a 2.2L Multi-mode GCI engine which was developed as part of a collaboration with Michigan Technological University, Hyundai and the US Department of Energy – Vehicle Technology Office under the funding award DE-EE0008478 [22]. The engine details are presented below in Table 2. The fuel flow rate map input was derived from the brake thermal efficiency map obtained from previous work by authors Zyada & Zoldak et al. [1]. Fuel flow measurement was conducted using the AVL 735S fuel mass flow meter and temperature controller. The measurement uncertainty of the flow meter was within 0.12% [23].

Vehicle Model Setup

The vehicle used in this work was based off a mid-sized SUV having the basic vehicle details as presented in Table 3.

TABLE 2 Engine details

Engine	4-Cyl Multi-mode GCI Engine
Displacement [L]	2.2
Bore [mm]	85.4
Compression Ratio [-]	16:1
Camshaft Arrangement	DOHC
Valve System	16 valves HLA, chain drive
Piston	Bowl in piston
Turbocharger	E-VGT
EGR	high pressure cooled EGR loop
Fuel Pressure [bar]	745
Fuel Type	US E10 Gasoline
Fuel Density (kg/m3)	745
Fuel Heating Value (MJ/kg)	42.9

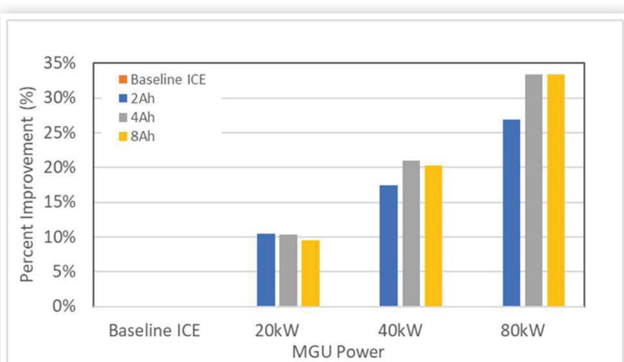
sizing and should be reviewed further to determine if there is any opportunity there for improvement.

Summary

In this study, an HEV operation strategy was proposed by combining a 2.2L Multi-mode GCI engine with an e-motor sizing (20 kW to 80kW) and the battery capacity (2Ah to 8Ah). For evaluation, a parametric GTDrive study assessed impact on fuel consumption. Other strategies used in the study included implementing start-stop, regeneration, gear shift optimization and downsizing of the engine, to assess the effects of these strategies on fuel economy improvement. The HEV powertrain with proposed strategies was optimized over FTP75 cycle. Final key results include:

- The fuel economy percent improvement over the 2.2L Multi-mode GCI engine baseline is presented for all the configurations as shown in Figure 18.
- The largest percent improvement was found with combining the 80kW MGU and both 4Ah and 8Ah battery capacity sizes. This is due to operating most of the driving cycle near the lowest BSFC operating region as shown in Figure 16.
- It is observed that for the 80kW MGU the residency of the engine speed and load is more concentrated in the high efficiency GCI mode area of the operating map namely 10 to 13bar BMEP and 1500rpm to 2000rpm. However, from Figure 17 the 80kW MGU only uses 1/3 of its overall torque supply and absorb capacity, which means it is under-utilized. This is likely due to the control strategy being based on torque limitation.
- If a power control strategy was utilized than perhaps the 40kW MGU would be better utilized and result in the multimode GCI engine being operated more in the optimal fuel economy island.
- The gear utilized during braking could also affect the optimization of the MGU power level and it is recommended that this be further reviewed in a subsequent study.

FIGURE 18 Percent improvement in fuel consumption over the FTP75 cycle compared to the baseline for all 9 configurations of MGU power and battery capacity.



Conclusions

Using the SOC Hunting strategy, the best sizing combination is an 80kW MGU with either a 4Ah or 8Ah battery. The 80kW MGU has a high enough torque limit to fully take advantage of regen-braking over the FTP75 drive cycle and can be used in EV only mode to drive the vehicle for significant periods. However, the 80kW MGU is underutilized due to the fact that a torque limiting strategy was employed and a recommendation for a power limiting strategy be studied to determine whether the 40kW MGU could be more adequately utilized to result in an overall improve in the multimode GCI ICE in its optimal fuel economy island. The 4Ah and 8Ah battery increases the amount of time available for EV only driving versus the 2Ah battery. The 8Ah battery has smaller capacity range at 25% versus the 4Ah battery which has 35% therefore the 8Ah battery will result in a longer life and improved durability.

The results showed that the FTP 75 cycle is less sensitive to battery size than MGU power, and MGU power needs to be carefully optimized and for drive cycle being considered (FTP75, NEDC, WLTP, highway and city combined cycles). The 80kW MGU with 4Ah or 8Ah battery results in 33% improvement FTP75 cycle fuel consumption of 4.66 L/100km compared to the baseline 2.2L multimode GCI ICE operation which resulted in 6.99 L/100km.

Improvements to this modeling study would include the use of a power control strategy as opposed to the torque limited strategy that was used in this work. The power control strategy would enable more appropriate use of each mode and thus be able to utilize the ICE in its optimal fuel economy region more extensively. Additionally reviewing the gear selected during downshifting could result in further improvements and could more readily utilize a smaller MGU size.

References

1. Zyada, A., Zoldak, P., Hollowell, J., Shirley, M. et al., "Demonstration of Better than Diesel Efficiency and Soot Emissions Using Gasoline Compression Ignition in a Light Duty Engine with Fuel Pressure Limitation," SAE Technical Paper 2021-01-0518 (2021), https://doi.org/10.4271/2021-01-0518.
2. Zyada, A., Zoldak, P., and Naber, J., "Development of Multiple Injection Strategy for Gasoline Compression Ignition High Performance and Low Emissions in a Light Duty Engine," SAE Technical Paper 2022-01-0457 (2022), https://doi.org/10.4271/2022-01-0457.
3. Wagh, M., Joo, N., Zoldak, P., Won, H. et al., "Real Fuel Modeling for Gasoline Compression Ignition Engine," SAE Technical Paper 2020-01-0784 (2020), https://doi.org/10.4271/2020-01-0784.
4. Sellnau, M., Hoyer, K., Moore, W., Foster, M. et al., "Advancement of GDCI Engine Technology for US 2025 café and Tier 3 Emissions," SAE Technical Paper 2018-01-0901 (2018), https://doi.org/10.4271/2018-01-0901.

5. Cung, K., and Ciatti, S., "A Injection Strategy to Achieve High Load Points for Gasoline Compression Ignition (GCI) Operation," Internal Combustion EngineDivision Fall Technical Conference, ASME 58318:V001T03A014, 2017.
6. Piehl, J.A., Zyada, A., Bravo, L., and Samimi, O., "Review of Oxidation of Gasoline Surrogates and its Components," *Journal of Combustion* 2018 (2018): 8406754, doi:10.1155/2018/8406754.
7. Kalghatgi, G., Agarwal, A.K., Goyal, H., and Houidi, M.B., "Introduction to Gasoline Compression Ignition Technology: Future Prospects," in: Kalghatgi, G., Agarwal, A.K., Goyal, H. and Houidi, M.B. (Eds), *Gasoline Compression Ignition Technology. Energy, Environment, and Sustainability*, (Singapore: Springer, 2022).
8. Zhu, S. and Naber, J., *Co-Optimized Mixed-Mode Engine and Fuel Demonstrator for Improved Fuel Economy while Meeting Emissions Requirements* (United States: N. p., 2022), doi:10.2172/1887341
9. Westbrook, C.K., "Chemical Kinetics of Hydrocarbon Ignition in Practical Combustion Systems," *Proceedings of the Combustion Institute* 28 (2000): 1563-1577.
10. Hyvönen, J., Haraldsson, G., and Johansson, B., "Operating Conditions Using Spark Assisted HCCI Combustion during Combustion Mode Transfer to SI in a Multi-Cylinder VCR-HCCI Engine," SAE Technical Paper 2005-01-0109 (2005), https://doi.org/10.4271/2005-01-0109.
11. Reuss, D.L., Kuo, T.-W., Silvas, G., Natarajan, V. et al., "Experimental Metrics for Identifying Origins of Combustion Variability during Spark-Assisted Compression Ignition," *International Journal of Engine Research* 9 (2008): 409-434.
12. Nakai, E., Goto, T., Ezumi, K., Tsumura, Y. et al., "MAZDA SKYACTIV-X 2.0L Gasoline Engine," in Proceedings of 28th Aachen Colloquium Automobile and Engine Technology 2019, October 7th-9th 2019, Aachen, 2019, 55–78.
13. Melaika, M., Mamikoglu, S., and Dahlander, P., "48V Mild-Hybrid Architecture Types, Fuels and Power Levels Needed to Achieve 75g CO2/Km," SAE Technical Paper 2019-01-0366 (2019), https://doi.org/10.4271/2019-01-0366.
14. Bao, R., Avila, V., and Baxter, J., "Effect of 48 V Mild Hybrid System Layout on Powertrain System Efficiency and its Potential of Fuel Economy Improvement," SAE Technical Paper 2017-01-1175 (2017), https://doi.org/10.4271/2017-01-1175.
15. EU, 2019, Regulation (EU) 2019/631 of the European Parliament and of the Council of 17 April 2019 setting CO2 emission performance standards for new passenger cars and for new light commercial vehicles, and repealing Regulations (EC) No 443/2009 and (EU) No 510/2011, OJ L 111, 25.4.2019, p. 13-53.
16. Zanelli, A., Millo, F., Barbolini, M., and Neri, L., "Assessment through Numerical Simulation of the Impact of a 48 V Electric Supercharger on Performance and CO2 Emissions of a Gasoline Passenger Car," SAE Technical Paper 2019-01-1284 (2019), https://doi.org/10.4271/2019-01-1284.
17. Conway, G., Chambon, P., and Alger, T., "Opportunities for Electrified Internal Combustion Engines," SAE Technical Paper 2020-01-0281 (2020), https://doi.org/10.4271/2020-01-0281.
18. Dadam, S.R., Jentz, R., Lenzen, T., and Meissner, H., "Diagnostic Evaluation of Exhaust Gas Recirculation (EGR) System on Gasoline Electric Hybrid Vehicle," SAE Technical Paper 2020-01-0902 (2020), https://doi.org/10.4271/2020-01-0902.
19. Ali, I., Zhu, D., and Kumar, V., "Effects of Differential Pressure Measurement Characteristics on High Pressure-EGR Estimation Error in SI-Engines," *International Journal of Engine Research* (November 2021), doi:10.1177/14680874211055580.
20. Kumar, V., Dadam, S.R., Zhu, D., and Mehring, J., "Fuel-Economy Performance Analysis with Exhaust Heat Recovery System on Gasoline Engine," *SAE International Journal of Engines* 15, no. 6 (2022): 825-847, https://doi.org/10.4271/03-15-06-0045.
21. Joshi, S., Dahodwala, M., Koehler, E.W., Franke, M. et al., "Trade-off Analysis and Systematic Optimization of a Heavy-Duty Diesel Hybrid Powertrain," SAE Technical Paper 2020-01-0847 (2020), https://doi.org/10.4271/2020-01-0847.
22. Zoldak, P., and Zhu, S., 'Hyundai Multi-Mode GCI Engine," Annual Merit Review-FY2021, US Department of Energy, Vehicle Technologies Office. Funding Award DE-EE008478, 2021.
23. AVL Website info for AVL 735S flow meter, https://www.avl.com/-/avl-fuel-mass-flow-meter-and-fuel-temperature-control, downloaded 12/27/2021.

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Abbreviations

BMEP - Compression Ratio
BMS - Battery Management System
BSFC - Brake Specific Fuel Consumption
BTE - Brake Thermal Efficiency
CI - Compression Ignition
CR - Compression Ratio
EGR - Exhaust Gas Recirculation
GCI - Gasoline Compression Ignition

GR - Gear Ratio
HCCI - Homogenous Charge Compression Ignition
HEV - Hybrid Electric Vehicle
ICE - Internal Combustion Engine
MCCI - Mixing-controlled compression ignition
MGU - Motor Generator Unit
NA - Naturally Aspirated
PPCI - Partially Premixed Compression Ignition
RON - Research Octane Number
SACI - Spark Assisted Compression Ignition
SI - Spark ignited
SIDI - Spark Ignited Direct Injection
SOC - State of Charge
SPCCI - Spark Controlled Compression Ignition
SUV - Sport Utility Vehicle
ULSD - Ultra-Low-Sulfur Diesel
Vmax - Vehicle Maximum Speed
WLTC - Worldwide Harmonized Light Vehicle Test Cycles

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