

Well-to-Wheels Analysis of the Greenhouse Gas Emissions and Energy Use of Vehicles with Gasoline Compression Ignition Engines on Low Octane Gasoline-Like Fuel

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ABSTRACT

Gasoline Compression Ignition (GCI) engines using a low octane gasoline-like fuel (LOF) have good potential to achieve lower NO_x and lower particulate matter emissions with higher fuel efficiency compared to the modern diesel compression ignition (CI) engines. In this work, we conduct a well-to-wheels (WTW) analysis of the greenhouse gas (GHG) emissions and energy use of the potential LOF GCI vehicle technology. A detailed linear programming (LP) model of the US Petroleum Administration for Defense District Region (PADD) III refinery system - which produces more than 50% of the US refined products - is modified to simulate the production of the LOF in petroleum refineries and provide product-specific energy efficiencies. Results show that the introduction of the LOF production in refineries reduces the throughput of the catalytic reforming unit and thus increases the refinery profit margins. The overall efficiency of the refinery does not change significantly because both the purchased energy and the refinery fuel production increase in response to the introduction of the LOF production. The refinery energy efficiency of LOF is approximately 0.8 and 1.6 percentage points higher than that of gasoline and diesel, respectively. Taking into account a 25% fuel economy gain relative to the regular gasoline internal combustion engine vehicle (ICEV), the per-mile-based WTW GHG emissions of the LOF GCI ICEV are estimated to be 22% and 9% lower than those of the today's gasoline and diesel ICEVs, respectively; and the per-mile-based WTW fossil energy use is 18% and 6% lower than gasoline and diesel ICEVs, respectively.

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INTRODUCTION

Internal combustion engines (ICEs) have become the major power sources for the transportation sector since the Industrial Revolution [1, 2, 3]. By ignition type, ICEs can be categorized into compression ignition (CI) engines and spark ignition (SI) engines that mostly use petroleum products: diesel for CI engines and gasoline for SI engines [4, 5]. Compared to gasoline SI engines, diesel CI engines are more efficient because of the high compression ratio (CR) and the low pumping losses. However, diesel CI engines suffer from higher tailpipe nitrogen oxides (NO_x) and particulate matter (PM) emissions that are relatively challenging to control by after-treatment devices, and sometimes compromise fuel efficiencies.

In the past ten years, a number of studies have been conducted to test the possibility of running diesel CI engines with gasoline-like fuels that do not ignite readily. In this gasoline compression ignition (GCI)

concept, a fuel in the gasoline autoignition range rather than the diesel fuel is injected into the diesel engine near the top of the compression stroke [1, 2, 3, 6]. Depending on the engine design, the optimum gasoline-like fuel for the GCI combustion will likely have a research octane number (RON) between 70 [7] and 85 [8]. This is a type of low octane gasoline-like fuel (LOF) compared to current gasoline on the market (RON ~91). Fuels with too low RON would have a short ignition delay so that there would be no difference from diesel fuels, while fuels with too high RON may have ignition challenges at low loads and high exhaust gas recirculation (EGR) levels [8].

GCI engines running on the LOF were reported to have the following advantages:

- First, the GCI combustion can achieve lower engine-out NO_x and lower PM emissions than conventional diesel CI engines. This has been demonstrated in both single-cylinder [9, 10, 11]

[12, 13, 14, 15] and multi-cylinder [16,17] CI engines, as well as in a demonstration vehicle with a four-cylinder CI engine [18]. Practical diesel fuels ignite very soon after its injection into the engine. Because the fuel does not have a chance to mix properly with air in the cylinder, the combustion occurs in fuel-rich mixture packets and leads to high NO_x and high PM formation. Compared to diesel fuels, the LOF has higher resistance to autoignition, and therefore, the autoignition of the LOF occurs significantly later after the start of the fuel injection. This ensures a much greater mixing of fuel and air before combustion, resulting in lower engine-out NO_x and low PM emissions at both the low and high loads [11,12,14].

- Second, GCI engines can at least achieve diesel-like fuel efficiency. Due to the low exhaust energy losses, lean operation, the low heat transfer, and the high CR, the fuel efficiency of LOF combustion in GCI engines are significantly higher than that of gasoline in today's SI engines. The indicated thermal efficiencies were reported to be as high as 56% and the combustion efficiencies can reach 98% in heavy-duty engines running at medium to full loads [7,15]. A detailed discussion about the fuel efficiency/economy of the LOF combusted in the GCI engine will be presented later in this paper.
- Third, the GCI engine cost could be lower than the modern CI engines [2,3]. On the one hand, mixing is dominated by the ignition delay for GCI engines rather than the injection event. Therefore, high injection pressure in modern diesel CI engines to promote premixing is not needed, reducing the cost of the injection system. On the other hand, the targets of the after-treatment devices are CO and hydrocarbons which are relatively easy to control through oxidation catalyst, avoiding the expensive and complicated technologies to reduce NO_x and PM.
- Fourth, the LOF GCI technologies may help consume excess light refinery components, mitigating the projected imbalance of the gasoline/diesel demand in the future. Although different organizations have different projections on the future energy in the transportation sector [19, 20, 21], the trends are similar that, in the next three decades, the global demand of fuels such as diesel and jet will continue to increase due to the development of the commercial transportation such as heavy on-road vehicle, aviation, marine, and rail, while gasoline demand will be relatively stable or even decrease because future gasoline cars are expected to be more efficient and may travel less distance [1]. Consequently, the ratio of (diesel+jet)-to-gasoline is projected to increase, implying the current configurations of the refineries may need to be adjusted to make more heavy fuels than gasoline. As a result, light refinery components with low octane numbers such as naphtha and straight run gasoline will inevitably need to find new use [2]. In this circumstance, new engine technologies such as GCI would help use these excess low octane gasoline-like fuels.

In recent years, significant progresses have been made in developing the LOF GCI technology. For example, the GCI engine has been designed and proved to be able to operate from as low as idle to as high as 20 bar brake mean effective pressure (BMEP) [22,23]; some vehicle demonstrations have also been made to test the drivability, emissions, and fuel economy of the vehicles with the GCI technology

[18,24]. However, there are still a number of roadblocks in the deployment of the commercial LOF GCI vehicles. On the GCI technology side, significant development work is needed to, for example, alleviate the combustion noise at high loads due to the high peak pressure rise rates, reduce the hydrocarbon and CO emissions at idle and low loads with advanced oxidation catalysts, ensure cold start, and avoid vapor lock [1]. On the LOF side, LOF is currently not a readily available fuel on the market. The lack of a common LOF specification base and the unknown LOF price prevents the engine/vehicle original equipment manufacturers (OEMs) from developing and optimizing the GCI engines and is difficult for refinery industries to determine the profit margins of the production and distribution of the LOF. In short, the commercializing of the LOF GCI technology needs close collaboration among regulators, refineries, engine/vehicle OEMs, and fuel retailers.

In addition to the advantages and challenges listed above, the GCI vehicles running on the LOF are expected to have lower greenhouse gas (GHG) emissions and energy use on a life-cycle basis than modern ICE vehicles (ICEVs) running on conventional and more upgraded products such as gasoline and diesel. The LOF may be mainly composed of naphtha streams in the refinery. These streams are less processed products compared to gasoline and diesel available on the market, implying a significant reduction in energy use and GHG emissions during the LOF production in the refinery [25]. Furthermore, the high fuel efficiency of the LOF in GCI engines would result in low energy use and GHG emissions during the vehicle operation as well.

In this work, we assess the GHG emissions and energy use associated with the production of the LOF in refineries and the use of the LOF in GCI vehicles in a life cycle perspective. A linear programming (LP) model representing the refinery industry of the US Petroleum Administration for Defense District Region III (PADD III) is configured to generate the LOF fuel with a RON of at least 70. Within the refinery, the detailed energy/material flows simulated by the LP model are allocated at the process unit level to derive the LOF refining energy intensity and GHG emissions. These results along with the GCI vehicle fuel economy gains determined from a literature review are further incorporated into the Argonne National Laboratory's Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET®) model [26] to evaluate the well-to-wheels (WTW) GHG emissions and energy use of the potential LOF GCI ICEV technology. We also show the comparison of the WTW results of the LOF GCI ICEV technology with the modern gasoline and diesel ICEVs.

METHODS AND DATA

System Boundary of the Life-Cycle Assessment

The GREET® model developed by Argonne National Laboratory [26] is used in this work to assess the WTW GHG emissions and the energy use of the LOF GCI ICEVs. GREET is a model widely used for analysis of life-cycle energy and environmental impacts of alternative and new transportation fuels and advanced vehicle technologies, and has become one of the essential tools used by researchers and policy makers in the US and abroad. In this study, carbon dioxide (CO_2)

methane (CH_4), and nitrous oxide (N_2O) are taken into account in GHG emissions, and their global warming potentials (GWP, 100-year perspective) are from the Fifth Assessment Report (AR5) of the United Nations Intergovernmental Panel on Climate Change (IPCC) [27], whereby 1 g of CO_2 , CH_4 , and N_2O corresponds to 1g, 30g, and 265 g of CO_2 -equivalent ($\text{CO}_2\text{-eq}$), respectively.

As illustrated in Figure 1, the system boundary for the life-cycle assessment (LCA) covers the whole WTW stage of vehicles with the LOF GCI technology, including the crude recovery (or crude oil production), transportation of crude to US refineries, the refining of crude to produce petroleum fuels including LOF, the transportation and distribution of LOF to the refueling stations, and the combustion of LOF in vehicles with GCI engines. Figure 1 also shows the boundaries for other terms mentioned in this work. In the following sections, we will describe the methods and key assumptions for the WTW stage.

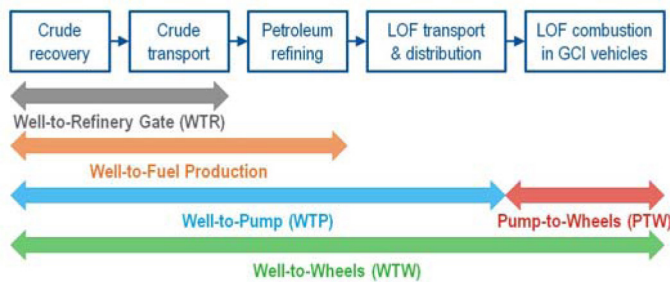


Figure 1. System boundary for the LCA of the LOF GCI technology

By now, because the LOF GCI technology has not been deployed in practical vehicles, ideally, the time frame of the analysis should focus on sometime in the future when GCI vehicles enter the market.

However, such analysis relies on the detailed vehicle market penetration study as well as justified projections of the future energy supply, refinery configuration, etc., which are beyond the scope of this study and may obscure the comparison of the LOF GCI ICEV with the modern gasoline and diesel ICEVs on a life-cycle basis. Therefore, for simplification, the time frame of the current analysis is set to be 2014, which is the most recent year for which most of necessary data are available.

Crude Recovery and Transportation

The crude oils processed in the US refineries are from various sources with different quantities and qualities. Table 1 shows the volume shares of crude oils received by US refineries and their API (American Petroleum Institute) gravities in 2014. The volume shares of crude oils by region and by type are estimated based on US domestic crude production and crude imports reported by Energy Information Administration (EIA) [28,29] and Canadian Association of Petroleum Products (CAPP) [30]. In general, the crude supplied to US refineries can be categorized into conventional crude, shale oil, and oil sands. In this work, the energy and GHG intensities of the recovery and the transportation processes of all three crude types are based on the GREET's default assumptions, and they are described in detail by Burnham et al. [31] for conventional crude oils, by Brandt et al. [32] and Ghandi et al. [33] for shale oil, and by Cai et al. [34] and Englander et al. [35] for oil sands.

Table 1. Volume shares, API gravity, and well-to-refinery gate (WTR) GHG emissions of crude oils received by the US refineries in 2014

Crude Sources—Types	Share (%)	API Gravity	WTR GHG ^a
US—Conventional	39.8	32.0	4.1
US—Shale Oil	11.9	45.3	7.4
Canada—Conventional	8.0	26.5	7.1
Canada—Oil Sands	9.6	17.6	25.6
Mexico—Conventional	5.1	26.5	4.6
Middle East—Conventional	12.4	31.8	6.8
Latin America—Conventional	9.4	24.8	4.9
Africa—Conventional	3.0	38.3	5.4
Others—Conventional	0.8	32.0	5.2
Energy-Weighted Average		30.7	7.3

^a Unit: g $\text{CO}_2\text{-eq}/\text{MJ}$.

Table 1 also shows the well-to-refinery gate (WTR) GHG emissions for each crude source, representing the GHG emission intensity in both the production of different types of crude oils and the transportation of these oils from different regions to the US refineries. On average, WTR GHG emissions of crude oils in the US refineries are estimated to be 7.3 g $\text{CO}_2\text{-eq}/\text{MJ}$ in 2014. However, they vary significantly among crude sources and types. For conventional crude oils, differences in WTR GHG emissions among crude sources reflect the differences in the energy intensity (i.e., energy use per unit of freight-distance hauled by transportation mode) of the mode and the distance of the crude transportation. For example, Canadian conventional crude oils are transported to the US through electricity-powered pipelines, the energy intensity (in MJ/ton-mile) of which is approximately 1.5 and 5.7 times higher than rails (for crude oils from Mexico) and ocean tankers (for crude oils from other non-US regions), respectively [36]. Although the energy intensity of rails is 3.9 times higher than ocean tankers, the relatively short transportation distance makes the WTR GHG emissions of the Mexican conventional oil lower than conventional oils from other non-US regions through ocean tankers. Conventional crude oils from Middle East have higher WTR GHG emissions than those from Latin America and Africa due to the longer transportation distances of the ocean tankers. In contrast to the conventional crude, WTR GHG emissions from crude production through the shale oil and the oil sands pathways are much higher. The high WTR GHG emissions of shale oil is mainly because of the significant amount of methane flaring and venting, especially for the Bakken Play [32]. Crude oil from Canadian oil sands has a WTR GHG emission of 25.6 g $\text{CO}_2\text{-eq}/\text{MJ}$, five times higher than the US conventional crude. This is mainly because the oil sands recovery processes such as oil sands extraction, bitumen separation, and bitumen upgrading are much more energy-intensive than conventional crude recovery processes [34].

Petroleum Refining

Refineries utilize a set of process units to convert crude oil into products such as gasoline, diesel, jet fuel, etc. In this study, a detailed LP model representing the “aggregated” US PADD III refinery industry is configured to generate the LOF with a RON of at least 70. The LP model simulates the refinery operation, the material flows between refining processes, the energy inputs and outputs, and the

refinery's technical and economic responses to the changes in the requirements of the petroleum products' specifications [37]. It maximizes refinery profit by determining the optimal volumetric throughput and utility balance (i.e., product slate, fuel gas, electricity, steam, etc.) among all units with the refinery under given market and technical constraints such as the prices of inputs and outputs, fuel specifications, regulations, etc. [38]. The outputs of the LP model provide detailed and optimized information about the refinery operation such as the overall margin and the estimated production, the utility requirements, product blending strategies, and the complete material flow in the system. These data can be further used to perform energy/material balance and allocation to derive product-specific efficiencies and feed shares for individual refinery products, which are the key parameters for the refining process in the GREET model.

Refinery LP Modeling Approach

As in similar works done in the past [38, 39, 40, 41], we use a LP model in this study to simulate the operation of the refinery if the LOF is introduced in the market. Data used in the LP model are obtained from IHSTM Energy (IHS). IHS maintains an extensive database on refineries worldwide, including process unit capacities, crude oil types imported by each country and refined products produced. The LP model is configured to represent the US refining system in the PADD III, which produces more than 50% of the US refined products [42]. The main outputs of the model are the optimal material and energy balances, as well as the properties of the finished products. These are all required to calculate the overall energy efficiency and the energy intensities of the individual refinery products.

Figure A1 in the Appendix shows the simplified diagram of the refinery that the LP model represents. The LP model is calibrated based on the average crude oil consumption and product demand of the PADD III in 2014. The crude slate, composed initially of dozens of crudes actually processed during that period, is reduced to nine proxy crudes in amounts that match the total processed crude quantity and average feed properties in terms of sulfur, specific gravity (SPG) and yields of representative cuts. The proxy crudes consumption rates are fixed, while other input materials such as natural gas and isobutane are left unconstrained. Additional imports of atmospheric residue and vacuum gas oil (VGO) are made available but limited to a maximum quantity.

Regarding the outputs, the multiple grades of gasoline and diesel produced during 2014 at the refineries of the different constituent areas of PADD III are also reduced to a limited number of proxy grades. All gasolines are modeled as blendstocks for oxygenate blending (BOB) which means that ethanol is not included in the final blend. BOB grades are divided into four main types, based on the combination of two criteria: conventional (CBOB) or reformulated (RBOB) according to their vapor pressure specification, and regular or premium according to their octane level requirements. Diesel grades are limited to two types, conventional and off-road diesel. Other model outputs include liquefied petroleum gas (LPG), naphtha and reformate for the petrochemical industry, jet fuel, high sulfur fuel oil (HSFO), lubes and waxes, asphalt, petcoke, and sulfur. Most of

the demands in finished products are either fixed or limited to a maximum amount. The demand of CBOB regular remains free, as it will be assumed as the blend displaced by the LOF.

Major CO₂ emission sources in the refinery include emissions from gas and heavy fuel burned onsite, catalytic coke burned at the fluid catalytic cracking (FCC) and residue FCC from catalyst regeneration, and CO₂ produced from the chemical reaction at the steam reforming (hydrogen production) plant. In addition, emissions from purchased energy that are used in refineries are also included.

Process unit capacities in the model are based on utilized rates of the installed capacities in 2014. The utilization rate is one of the levers used for calibration of the model. The current study does not assume any capital investment in additional process unit capacities.

The calibrated LP model representing the refinery industry in the US PADD III is further modified to generate the LOF used for the GCI combustion. The LOF is modeled as a separate blend sharing the same available blendstocks with other BOB grades. Table 2 compares the specification constraints of the LOF blend and the CBOB regular blend used in the LP model. GCI LOF has less stringent constraints for not only RON, but also the maximum Reid vapor pressure (RVP) and the evaporated fractions at different temperatures. The RVP constraint of the GCI LOF is determined by taking into consideration of both the lower inflammability limit and the evaporative emission standard of the gasoline fuel. Other property specifications of the LOF such as sulfur, olefins and aromatics are compliant with those of the gasoline available on the market (i.e., BOB after ethanol blending). In this work, we assume the production rate of the LOF is equal to 15% of the estimated CBOB regular production. The price set used for the optimization is based on information provided by IHS Energy. The selling price of the GCI LOF is assumed equal to the price of CBOB regular. Refinery CO₂ emissions are not subject to any penalty cost in the objective function.

Table 2. Comparison of the specification constraints of the GCI LOF and the CBOB regular

Property	Limits for the GCI LOF	Limits for the CBOB Regular
Octane Number ^a	RON ≥ 70	AKI ≥ 84, MON ≥ 80
RVP	5.5–15 psi	5.1–11.5 psi
Evaporation Rate	None	160 °F, ≥ 5 % by volume
		212 °F, ≥ 20 % by volume
		300 °F, ≥ 65 % by volume
SPG	0.720–0.783	0.715–0.775
Sulfur	≤ 10 ppm by weight	≤ 33 ppm by weight
Aromatics	≤ 35 % by volume	≤ 38.9 % by volume
Olefins	≤ 18 % by volume	≤ 22.2 % by volume
Benzene	≤ 0.62 % by volume	≤ 0.689 % by volume

^a RON: research octane number. MON: motor octane number. AKI: Anti-knock index = (RON+MON)/2.

Process-Level Energy Allocation within the Refinery

It has been reported that energy use and GHG emissions calculated for individual refinery products based on aggregated refinery level allocation are significantly different from those based on refinery

process-level allocation because refinery-level allocation ignores the fact that different products go through different process units within a refinery [25,43]. Therefore, process-level allocation is suggested to be used in the life-cycle analysis to take into account the differences in energy and emission associated with producing individual fuels [25]. In our previous work, we reported a refining-process-level-based method to capture process-dependent characteristics of fuel production within the refinery and allocate energy use of individual refining processes to refinery products [25,38,39,40,41]. In this work, a similar approach is adopted and briefly described below.

For a refining process with a number of feed streams (intermediate products or feedstocks) and yield streams (intermediate or final products), the energy burden (EB) of a specific refinery input i (feedstocks or energy inputs to the refinery, e.g., crude oils, isobutane, fuel oil, purchased natural gas, electricity, etc.) to produce per unit energy of yield stream j can be calculated by the following equation:

$$EB_{i,j} = \left(\sum_k F_k \cdot EB_{i,k} \right) \cdot \frac{W_j}{Y_j} \quad (1)$$

Where,

F_k = energy in the k^{th} feed stream to the process

Y_j = energy in the j^{th} yield stream from the process

$EB_{i,j}$ = embedded energy burden of the i^{th} refinery input to produce per unit energy of the j^{th} yield stream

$EB_{i,k}$ = embedded energy burden of the i^{th} refinery input to produce per unit energy of the k^{th} feed stream

W_j = allocation weighting factor for the j^{th} yield stream

W_j is the allocation weighting factor, and it could be the energy, the mass, or the market value percentage share of the j^{th} yield stream to all yield streams [25]. In this work, we use the most commonly used energy-based weighting factors because (1) mass-based allocation is not applicable due to the presence of the electricity inputs and generations, (2) the differences between energy-based and market-value-based allocation in derived product-specific efficiencies were reported to be not significant for major refinery products [38], and (3) energy values are the most important specification for most petroleum fuels. The energy-based W_j can be expressed as:

$$W_j = Y_j / \sum_j Y_j \quad (2)$$

Therefore, Eq. (1) can be further simplified as:

$$EB_{i,j} = \left(\sum_k F_k \cdot EB_{i,k} \right) / \sum_j Y_j \quad (3)$$

Based on the detailed LP modeling results, the above energy allocation method is conducted for all processes in the refinery, and thus the energy burdens of individual refinery inputs to produce per unit energy of each stream (including intermediate and final products) are obtained. For a yield stream j , the sum of energy burdens of all refinery inputs is defined as the energy intensity (EI) of the yield stream j , representing the total purchased energy that contributes to the production of per unit energy of the stream j :

$$EI_j = \sum_i EB_{i,j} \quad (4)$$

If the stream j is a final refinery product (e.g., LOF, gasoline, diesel, etc.), Eq. (4) will result in the product-specific energy intensity for that final product, and the inverse of EI_j is defined as the product-specific refining energy efficiency (η):

$$\eta_j = 1/EI_j = 1 / \sum_i EB_{i,j} \quad (5)$$

It should be noted that the sulfur product from the sulfur plant is considered a waste in our analysis and assumed not to receive any energy during the allocation. We therefore distribute sulfur plant's energy burdens among gasoline, diesel, and LOF pools by their energy values because they are the main refinery products requiring sulfur removal.

The material flows among refinery processes provided by the LP model are in the mass unit with the exception of electricity. To conduct energy-based allocation, we convert the mass flows to the energy flows by using each stream's lower heating value (LHV). For solid and gaseous products, LHVs used in the GREET model [26] and by Green and Perry [44] are applied, respectively. For liquid streams, we first estimate the higher heating values (HHV) on the basis of the following equations [40,45]:

$$HHV = 17672 + 66.6 \cdot API - 0.316 \cdot API^2 - 0.0014 \cdot API^3 \quad (6)$$

$$API = 141.5 / SPG - 131.5 \quad (7)$$

Where,

HHV = higher heating value, in Btu/lb

API = API gravity

SPG = specific gravity, provided by the LP model

HHVs are further converted to LHVs by multiplying by a factor of 0.94, which is the average LHV-to-HHV ratio of liquid petroleum products in the GREET model [40].

LOF Combustion in GCI ICEV -Fuel Economy Gains

GHG emissions from fuel combustion are normally the largest emission sources in the LCA of a petroleum transportation fuel. They can be accurately estimated through the carbon balance if the vehicle fuel economy (FE) is known. In this work, the FE gain of the LOF GCI internal combustion engine vehicle (ICEV) is determined from a literature review of gasoline-like fuels combusted in the GCI engines.

Because of the low exhaust loss and the low heat transfer, GCI engines burning gasoline-like fuels can achieve high fuel efficiencies [1,3,18,46,47]. The indicated thermal efficiencies (η_{thermal}) and the combustion efficiencies of gasoline-like fuels with a research octane number (RON) spanning from 69 to 99 were reported to be higher than 56% and 98%, respectively, in heavy-duty CI engines running at medium to full load [7,15]. Using a single-cylinder engine with RON91 gasoline, Sellnau et al. [46] found that the GCI combustion strategy achieved about 8% greater η_{thermal} and about 14% lower specific CO₂ emissions relative to diesel baseline tests on the same engine, demonstrating the good potential for fuel economy. Yang et al. [6] tested the combustion of the straight-run naphtha in the multiple premixed and the partially premixed CI modes on a single cylinder diesel engine, and they found that the indicated specific fuel consumption (SFC) of the straight-run naphtha CI modes was about 30% lower than that of the diesel CI mode at the engine speed >1600 rpm. With a single cylinder SI direct injection (SIDI) engine running at a CR of 12:1, Chang et al. [48] demonstrated that weighted driving cycle average SFC were improved significantly by 19% when the engine was run in the partially premixed CI mode using heavy naphtha compared to in the SI mode using RON91 gasoline. Later, they developed a more optimized combustion chamber with higher CR of 14:1 to improve ideal and light load combustion stability [49]. With the new design, they achieved 26% average SFC reduction with light naphtha compared to conventional SI operation on RON91 gasoline over a range of part load operating points of the federal test procedure (FTP) city cycle. Viollet et al. [50] further evaluated the effects of CR on the operation of the CI mode in a single cylinder SI engine for both light and heavy naphtha, and they found that the SFC improvements over SI operation with RON91 gasoline vary from 15% to 26% for light naphtha and 18% to 23% for heavy naphtha. With a multi-cylinder CI engine running on 87 AKI gasoline, Kolodziej et al. [51] analyzed the GCI engine operation at low speed and low load portion of the engine map. By updating the experimental engine data in Autonomie vehicle simulations, they predicted the combined vehicle fuel economy of the GCI engine was 28.7% higher than the baseline port fuel injection (PFI) gasoline engine. Very recently, Sellnau [24] reported a vehicle test result of a Hyundai Sonata equipped with the Generation 1 GCI engine. Compared to the baseline 2.4 L PFI gasoline engine, the GCI engine achieved a 42.5% and 33.5% better fuel economy in city (federal test procedure-75, FTP-75) and highway (highway fuel economy test, HWFET) driving cycles, respectively, resulting in a combined improvement of 39.3%.

As mentioned above, the efficiency benefit of the GCI engine was reported in different metrics relative to either gasoline or diesel in previous studies. These metrics include η_{thermal} (the engine work

output per unit of chemical energy input) and SFC (the mass of fuel required per unit of work output). They have a relationship with FE-the distance that can be traveled per unit gasoline-equivalent volume of fuel, in e.g., mile-per-gallon gasoline-equivalent (MPGGE)-as the following equation [52]:

$$FE \propto \eta_{\text{thermal}} = 1/\text{SFC}/\text{LHV} \quad (8)$$

Here, we assume the LHVs of RON91 gasoline (approximately E10, petroleum gasoline blended with 10% ethanol by volume) and diesel are 41.7 and 42.6 MJ/kg, respectively [26]; the FE ratio of diesel CI ICEVs to E10 SI ICEVs is 1.2 [26]; and all other vehicle parameters are same for all studies. Using Eq. (8) and the LHVs of gasoline-like fuels specifically provided in each study, the MPGGE FE gains of the GCI ICEV relative to the regular E10 SI ICEV can be estimated. As summarized in Table 3, previous driving-cycle-based studies suggested that the MPGGE FE of the GCI ICEVs could be 120%-139% of the regular E10 SI ICEVs with a mean of ~130%. It should be noted that the results were mostly based on either experimental estimations or vehicle simulations with limited number of steady-state data points. The only chassis testing results reported by Sellnau [24] of Delphi Inc. claimed that emissions were higher than targets. Delphi Inc. has also developed a newer generation of GCI engine with significant improvement in fuel economy [24]. However, no quantitatively driving-cycle-based vehicle fuel economy is reported. Considering the efficiency losses to meet the emission regulations and other vehicle requirements, we therefore assume a 25% vehicle FE gain for the GCI technology relative to regular E10 vehicles. We also take into account a FE gain range of 15%-40% in this study to evaluate the effect of the FE gain assumption on the WTW GHG emissions and energy use of the GCI ICEV. Note that the FE of regular E10 SI ICEVs is improving over time due to various technology advances such as vehicle light-weighting, aerodynamic drag reduction, tire rolling resistance reduction, etc. The estimated 25% FE gain for the GCI ICEV (as well as its range of 15%-40%) is applied on top of the FE of the regular E10 SI ICEV regardless its FE improvement in the future.

Table 3. Summary of fuel specifications, engine efficiency/fuel consumption gains, and estimated MPGGE fuel economy gains of the GCI vehicle relative to the regular E10 gasoline vehicle from driving-cycle-based studies

References	RON	LHV (MJ/kg)	CR	Comments	FE Gains
Chang et al. [49] ^a	68	41.4	14	SFC 26% < E10	37.0%
Viollet et al. [50] ^a	68	41.4	13	SFC 23% < E10	31.1%
Viollet et al. [50] ^a	68	41.4	14	SFC 26% < E10	35.9%
Viollet et al. [50] ^a	— ^d	44.6	13	SFC 23% < E10	20.8%
Viollet et al. [50] ^a	— ^d	44.6	14	SFC 22% < E10	20.4%
Kolodziej et al. [51] ^b	92.6	— ^c	17.5	— ^c	28.7% ^f
Sellnau et al. [24] ^c	91	— ^c	15	— ^c	39.3% ^f

^a FTP-75 cycle, estimated based on 6 steady-state engine points. ^b Unadjusted combined UDDS (urban dynamometer driving schedule) and HWFET cycles, Autonomie vehicle simulation based on 29 steady-state engine operating points. ^c Unadjusted combined UDDS and HWFET cycles, chassis testing results. ^d Heavy naphtha. ^e Not reported. ^f Reported in the literature directly.