Applied Energy 181 (2016) 391–398

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Compression ignition of low-octane gasoline: Life cycle energy consumption and greenhouse gas emissions

Han Hao, Feiqi Liu, Zongwei Liu, Fuquan Zhao *

State Key Laboratory of Automotive Safety and Energy, Tsinghua University, Beijing 100084, China

HIGHLIGHTS

- A process-based, well-to-wheel conceptualized life cycle assessment model is established.
- The impacts of using low-octane gasoline on compression ignition engines are examined.
- Life cycle energy consumption and GHG emissions reductions are 24.6% and 21.6%.
- Significant technical and market barriers are still to be overcome.

ARTICLE INFO

Article history:
Received 12 May 2016
Received in revised form 16 August 2016
Accepted 17 August 2016

Keywords:
Vehicle technology
Low-octane gasoline
Gasoline compression ignition
Energy consumption
GHG emissions
Life cycle assessment

ABSTRACT

The use of low-octane gasoline on Gasoline Compression Ignition (GCI) engines is considered as a competitive alternative to the conventional vehicle propulsion technologies. In this study, a process-based, well-to-wheel conceptualized life cycle assessment model is established to estimate the life cycle energy consumption and greenhouse gas (GHG) emissions of the conventional gasoline-Spark Ignition (SI) and low-octane gasoline-GCI pathways. It is found that compared with the conventional pathway, the low-octane gasoline-GCI pathway leads to a 24.6% reduction in energy consumption and a 22.8% reduction in GHG emissions. The removal of the isomerization and catalytic reforming units in the refinery and the higher energy efficiency in the vehicle use phase are the substantial drivers behind the reductions. The results indicate that by promoting the use of low-octane gasoline coupled with the deployment of GCI vehicles, considerable reductions of energy consumption and GHG emissions in the transport sector can be achieved. However, significant technical and market barriers are still to be overcome. The inherent problems of NO_x and PM exhaust emissions associated with GCI engines need to be further addressed with advanced combustion techniques. Besides, the yield of low-octane gasoline needs to be improved through adjusting the refinery configurations.

1. Introduction

The road transport sector, represented by the wide-spread billions of on-road vehicles globally, is the essential element of modern society. Driven by sustained economic growth, global vehicle market experienced rapid growth over the past decades. Total passenger vehicle sales increased from 29 million in 1980 to 65 million in 2014 [1]. Accordingly, global vehicle stock reached 1.2 billion in 2014, implying a vehicle ownership level of 180 vehicles/1000 people [2]. Considering the huge market potentials in emerging economies such as China and India, global vehicle sales is expected to maintain the increasing trend in the coming decades [3].

The fast-growing vehicle ownership has caused great energy and environmental concerns. Vehicles are the major consumers of gasoline and diesel. As reported by the Intergovernmental Panel on Climate Change (IPCC), around half of global oil consumption can be attributed to the transport sector [4]. Regarding CO_2 emissions, the transport sector was responsible for around 23% of

Abbreviations: CI, Compression Ignition; EPA, Environmental Protection Agency; GCI, Gasoline Compression Ignition; GHG, Greenhouse Gas; HHV, high heating value; IEA, International Energy Agency; IPCC, Intergovernmental Panel on Climate Change; LCA, life cycle assessment; LHV, low heating value; MPCI, Multiple Premixed Compression Ignition; PDCI, Partially Diffused Compression Ignition; PPCI, Partially Premixed Compression Ignition; RON, Research Octane Number; SI, Spark Ignition; TtW, Tank-to-Wheel; WtT, Well-to-Tank; WtW, Well-to-Wheel.

* Corresponding author.
E-mail address: zhaofuquan@tsinghua.edu.cn (F. Zhao).

http://dx.doi.org/10.1016/j.apenergy.2016.08.100
0306-2619/

global energy-related CO_2 emissions in 2013 [5]. In addition, vehicles are the major emitters of air pollutants such as NO_x, PM, HC and CO, which have caused severe urban environmental degradations [6].

To cope with these challenges, vehicle and fuel technologies with better energy and environmental impacts are being sought as alternative to conventional technologies [7–11]. Among the potential alternative technologies, the use of low-octane gasoline on Gasoline Compression Ignition (GCI) engines is considered as a promising technology pathway. From the fuel perspective, low-octane gasoline normally refers to gasoline with Research Octane Number (RON) of lower than 70. As a comparison, the RON of conventional gasoline for car use is generally higher than 90. Typical types of low-octane gasoline include naphtha, raffinate oil, etc. The major components of low-octane gasoline are short-chain hydrocarbons, for which low-octane gasoline exhibits both high volatility and low RON. Low-octane gasoline cannot be used on conventional Spark Ignition (SI) engines, because its low RON leads to engine knock [12]. But it is less reactive than diesel to allow the combustion of Compression Ignition (CI) engines to be more premixed [13]. From the engine perspective, CI engines are conventionally fueled with diesel. With the developments of mechanical and electronic technologies, more precise controls of fuel injection and engine work become possible. This allows for some advanced combustion modes such as Partially Premixed Compression Ignition (PPCI) [14], Multiple Premixed Compression Ignition (MPCI) [15,16], and Partially Diffused Compression Ignition (PDCI) [17]. These technologies have made the concept of GCI engine, i.e. using gasoline on CI engines, possible [18,19].

As an alternative to the conventional gasoline-SI and diesel-CI technologies, the low-octane gasoline-GCI technology contributes to addressing the following issues. First, the thermal efficiency of GCI engines is much higher than the conventional SI engines, which can significantly reduce the fuel consumption of gasoline vehicles [12]. Second, the gasoline refining processes can be simplified. Specifically, the processes for producing high-octane gasoline out of low-octane gasoline, mostly the isomerization and catalytic reforming units, can be saved. This benefits the refinery comprehensively in energy, environmental and economic terms. Third, the GCI technology offers the ability to balance gasoline and diesel consumptions. Globally, the demand for gasoline is becoming saturated, especially with the saturation of car ownership and the penetration of electric cars [20]. Alternatively, driven by sustained economic development, the demand for diesel is expected to grow continuously [21,22]. Under such a circumstance, the diesel/gasoline demand ratio will potentially grow to a high level that the refinery side cannot meet. By deploying GCI engines, gasoline can be used as alternative to diesel in a flexible amount. This helps to maintain the diesel/gasoline demand ratio at a rational level.

Despite of the advantages mentioned above, the major drawbacks of low-octane gasoline-GCI technology are the increase in engine cost and the exhaust emissions issues. Due to both structure change and the application of advanced control technologies, the cost of GCI engines can be significantly higher than conventional SI engines. However, regarding the more and more stringent fuel consumption standards for passenger vehicles [23], the increase in cost has become the essential condition to meet the standards. Besides, GCI engines face the inherent problems of NO_x and PM exhaust emissions, even though the development of advanced combustion techniques has largely addressed this concern.

Preliminary researches have been conducted to explore the performances of using low-octane gasoline on GCI engines. Saudi Aramco performed bench tests using naphtha on PPCI engine and compared the results with conventional gasoline-SI operation. The tests were conducted under different compression ratios, loads and piston bowl geometries [24–27]. The results indicated that the use of naphtha on PPCI engine can meet all the emissions, noise and transient operation requirements, and at the same time, maintain high efficiency. Furthermore, Saudi Aramco expected that the simplification of refining processes will further reduce energy consumption and emissions from the fuel production stages. Sinopec performed similar tests by using raffinate oil, another kind of low-octane gasoline with low aromatics [28]. The tests also indicated a significant improvement of fuel economy. Despite these research progresses, existing studies mostly focused on the vehicle-level impacts. Energy consumption and Greenhouse Gas (GHG) emissions have rarely been examined from the life cycle perspective. Employing the life cycle perspective is extremely important for this technology as it has substantial impacts both on the vehicle side and the refinery side.

With the aim of filling such a gap, this study evaluates the energy consumption and GHG emissions of using low-octane gasoline on GCI engines from the life cycle perspective, and compares the results with the conventional gasoline-SI pathway. This study aims to answer, to what extent can low-octane gasoline-GCI technology reduce energy consumption and GHG emissions, and whether these benefits compensate the engine cost increment. The whole paper is organized as follows. After this introduction section, the methods and data employed in this study are introduced. Following that, the results are discussed. The subsequent section presents the policy implications. The final section concludes the whole study.

2. Methods and data

2.1. System boundary

As mentioned above, this study compares the life cycle energy consumption and GHG emissions between the conventional gasoline-SI pathway and the low-octane gasoline-GCI pathway. Fig. 1 illustrates the processes within a typical oil refinery. In the refinery, different intermediate products are simultaneously derived from crude oil. Many types of intermediate products from different units are blended to produce particular finished products [29].

Low-octane gasoline can be derived through multiple pathways, including naphtha (highlighted in the red boxes), raffinate oil, etc. Considering fuel representativeness and data availability, naphtha is chosen as the low-octane gasoline to be compared in this study. The counterpart high-octane gasoline to be compared is the corresponding output of naphtha isomerization and catalytic reforming, as highlighted in the blue boxes. Several studies have investigated the physicochemical properties of naphtha used as motor fuel [24,30–32]. The reported physicochemical properties of the conventional gasoline and naphtha are compared in Table 1. The naphtha defined in this study can be considered as a mixture of Aramco heavy naphtha and light naphtha [24].

In this study, the system boundary is defined by referring to the Well-to-Wheel (WtW) concept, as shown in Fig. 2 [33]. Energy consumption and GHG emissions associated with crude oil extraction, transportation, fuel refining, transportation and vehicle use are taken into consideration. Furthermore, crude oil extraction, transportation, fuel refining, transportation are categorized into the Well-to-Tank (WtT) phase; vehicle use into the Tank-to-Wheel (TtW) phase. The major inputs into this system include crude oil, process fuels, electricity, steam, etc. The major outputs of this system include air pollutants, GHG emissions, etc. It should be noted that energy consumption and GHG emissions associated with refinery infrastructure construction, equipment manufacturing and vehicle manufacturing are not covered in the analysis.

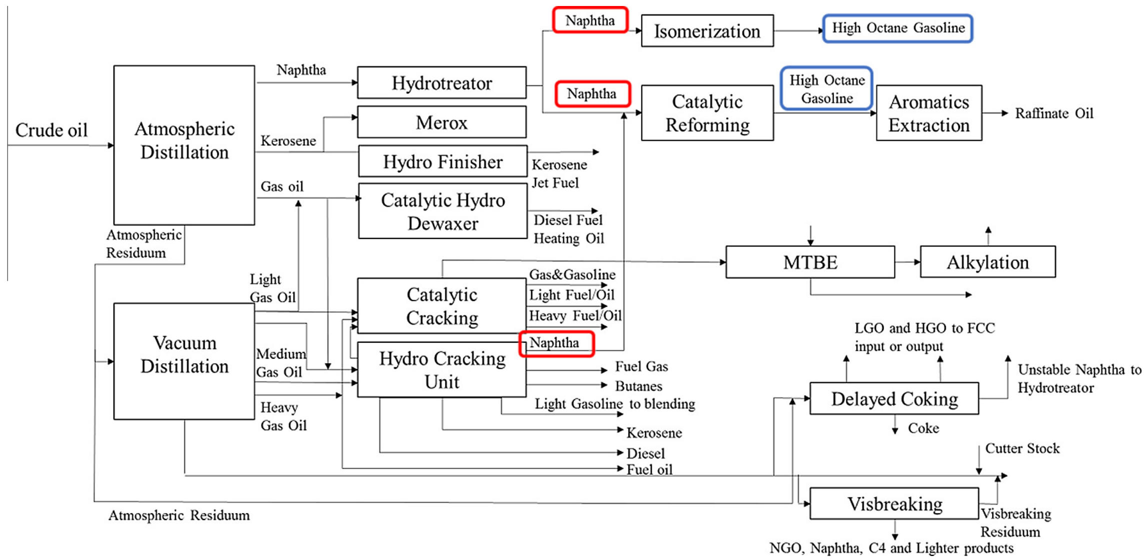

Fig. 1. Typical crude oil refining processes.

Table 1
Physicochemical properties of conventional gasoline and naphtha.

	Unit	Conventional gasoline [24]	Aramco heavy naphtha [24]	Aramco light naphtha [24]
RON	–	93	62	66
Density	kg/m^3	0.74	0.73	0.66
HHV	MJ/kg	42.3	45.2	42.6
LHV	MJ/kg	41.9	44.9	42.2
Normal paraffins	%	20.8	34.8	53.3
Isoparaffins	%	30.3	35.3	39.6
Aromatics	%	30.6	11.5	0.9
Naphthenes	%	4.5	17.9	6.2
Olefins	%	0.9	0.5	0.0
Oxygenates	%	12.3	0.0	0.0
Sulfur	ppm	17.3	<20	<20
Distillation	°C	40–160	80–160	30–80

2.2. Methods

The refinery produces multiple products in a single chemical process or combined chemical processes [34]. The allocation of energy consumption and GHG emissions in the refinery can be conducted at either the refinery level or the refining process level. Furuholt demonstrated that refining process-based allocation is the suitable method for calculating energy consumption and GHG emissions when dealing with individual refinery products [35]. In this study, the refining process-based allocation method is applied.

For a certain refining process, the allocation of energy consumption and GHG emissions can be based on different methods. Wang compared the allocations of energy consumption and emissions to refinery products based on mass, energy content and market value methods [36,37]. The density method has also been used to estimate the cost of gasoline based on a process model [29]. Among these methods, the mass-based method provides significant engineering perspective for energy allocation. In this study, the commonly used mass-based allocation method is applied. The process energy consumptions within the refinery, including process fuel, electricity and steam consumptions, are calculated by using Eq. (1).

$$EC_n = \left[\sum_p \left(\sum_i E_{p,i,n} \cdot \prod_i Y_{p,i}\right)\right] \Big/ \left[\sum_p \left(\prod_i Y_{p,i}\right) \cdot LHV\right] \quad (1)$$

where
EC_n — process energy n consumption attributed to target fuel production (MJ/MJ for process fuels; kW h/MJ for electricity; kg/MJ for steam);
$E_{p,i,n}$ — process energy n consumption of production pathway p refining unit i (MJ/kg for process fuels; kW h/kg for electricity; kg/kg for steam);
$Y_{p,i}$ — the yield ratio of target fuel from production pathway p refining unit i;
LHV — the low heating value of the target fuel (MJ/kg).

Eqs. (2) and (3) calculate the total energy consumption and GHG emissions of the refining stage based on the obtained process energy consumptions.

$$EC_{refining} = \sum_n EC_n \cdot CF_n \quad (2)$$

$$GE_{refining} = \sum_n EC_n \cdot EF_n \quad (3)$$

where
$EC_{refining}$ — energy consumption of the refining stage (MJ/MJ);
$GE_{refining}$ — GHG emissions from the refining stage (g $CO_{2,e}$/MJ);

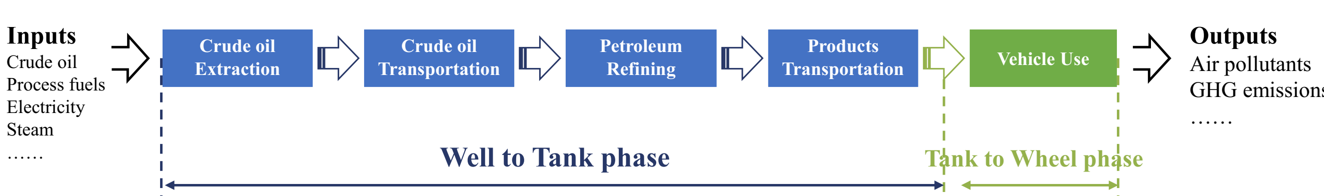

Fig. 2. System boundary defined in this study.

CF_n — primary energy conversion factor for process energy n (MJ/MJ for process fuels; MJ/kW h for electricity; MJ/kg for steam);
EF_n — GHG emissions factor for process energy n (g $CO_{2,e}$/MJ for process fuels; g $CO_{2,e}$/kW h for electricity; g $CO_{2,e}$/kg for steam).

Eqs. (4) and (5) are used to estimate the energy consumption and GHG emissions from the fuel production stages.

$$EC_{production} = EC_{ex} + EC_{oil-trans} + EC_{refining} + EC_{product-trans} \tag{4}$$

$$GE_{production} = GE_{ex} + GE_{oil-trans} + GE_{refining} + GE_{product-trans} \tag{5}$$

where
$EC_{production}$ — the energy consumption of the fuel production stages (MJ/MJ);
EC_{ex} — the energy consumption of the crude oil extraction stage (MJ/MJ);
$EC_{oil-trans}$ — the energy consumption of the crude oil transportation stage (MJ/MJ);
$EC_{product-trans}$ — the energy consumption of the product transportation stage (MJ/MJ);
$GE_{production}$ — the GHG emissions from the fuel production stages (g $CO_{2,e}$/MJ);
GE_{ex} — the GHG emissions from the crude oil extraction stage (g $CO_{2,e}$/MJ);
$GE_{oil-trans}$ — the GHG emissions from the crude oil transportation stage (g $CO_{2,e}$/MJ);
$GE_{product-trans}$— the GHG emissions from the product transportation stage (g $CO_{2,e}$/MJ).

The energy consumption and GHG emissions from the WtT phase are determined by Eqs. (6) and (7).

$$EC_{wtt} = EC_{production} \times FCR \tag{6}$$

$$GE_{wtt} = GE_{production} \times FCR \tag{7}$$

where
EC_{wtt} — the energy consumption of the WtT phase (MJ/km);
GE_{wtt} — the GHG emissions from the WtT phase (g $CO_{2,e}$/km);
FCR — the vehicle fuel consumption rate (MJ/km).

Energy consumption and GHG emissions from the TtW phase are determined using Eqs. (8) and (9). The GHG emissions from this phase can be calculated by using the carbon content of the vehicle fuel.

$$EC_{ttw} = FCR \tag{8}$$

$$GE_{ttw} = EF_{fuel} \times FCR \tag{9}$$

where
EC_{ttw} — the energy consumption of the TtW phase (MJ/km);
GE_{ttw} — the GHG emissions from the TtW phase (g $CO_{2,e}$/km);
EF_{fuel} — the GHG emissions factor of vehicle fuel (g $CO_{2,e}$/MJ).

The life cycle energy consumption and GHG emissions can be obtained by combing the results from WtT and TtW phases, as Eqs. (10) and (11) show.

$$EC_{wtw} = EC_{wtt} + EC_{ttw} \tag{10}$$

$$GE_{wtw} = GE_{wtt} + GE_{ttw} \tag{11}$$

where
EC_{wtw} — the life cycle energy consumption of the technology pathway (MJ/km);
GE_{wtw} — the life cycle GHG emissions from the technology pathway (g $CO_{2,e}$/km).

2.3. Data

2.3.1. WtT phase

The yields of target products and the energy consumptions of the relevant refining units are the essential data for calculating the energy consumption and GHG emissions from the oil refining stage. For different refineries, the types and amounts of refining products vary considerably depending on many factors [38]. The yield ratios used in this study is based on data from a representative Chinese oil refinery [39–41]. The yield ratios of target products from the relevant refining units are shown in Table 2.

Energy consumptions of the relevant refining units are derived from reference [42], as presented in Table 2. The energy consumptions are further categorized into process fuel, electricity and steam consumptions. Regarding process fuels, the reference did not specify the fuel types. Considering the fact that the majority of process fuels consumed in refineries are natural gas [43], all process fuels are calculated as natural gas in this study. Regarding electricity and steam, they can be produced internally by refineries or purchased from external sources. The primary energy conversion factors and GHG emissions factors of electricity and steam used in this study are based on references [44–46]. Based on the assumptions above, the primary energy conversion factors of electricity and steam are 9.49 MJ/kW h and 2.13 MJ/kg; GHG emissions factors of process fuels, electricity and steam are 68.9 g $CO_{2,e}$/MJ, 1042.6 g $CO_{2,e}$/kW h and 233.9 g $CO_{2,e}$/kg, respectively. It should be noted that in an effort to simplify the calculations, hydrogen production is not considered in the calculation.

Regarding the stages of oil extraction, transportation, and product transportation, there is little difference between conventional gasoline and low-octane gasoline pathways. Thus, the same energy consumptions and GHG emissions are applied to both conventional gasoline and low-octane gasoline pathways, as detailed in Table 4 [47,48].

2.3.2. TtW phase

Regarding the TtW phase, Saudi Aramco has performed multiple sets of bench tests of using low-octane gasoline on PPCI engines [24–27]. The test conditions and results are summarized in Table 3. These data are employed as the basis for estimating energy consumption and GHG emissions from the TtW phase in this study.

For each test, the fuel consumption rates were tested at different steady-state points. The comprehensive fuel consumption rate is the weighted average of the fuel consumption rates at all tested points. In different bench tests, the test conditions such as the RON of the tested fuel, compression ratio were changed. It can be found that when fixing the engine compression ratio, the fuel economy improves by reducing the RON of tested fuel. When fixing the RON of the tested fuel, the fuel economy improves by increasing the engine compression ratio. The average fuel saving compared with conventional gasoline-SI engine is around 20%, which is used as the estimation for this study.

Regarding the real-world vehicle fuel consumption rate, the fuel consumption rate of the conventional gasoline-SI vehicles is assumed to be 6.9 L/100 km, the average level of China's new passenger vehicles in 2015 [49] (equivalent to 2.14 MJ/km). The fuel saving of low-octane gasoline-GCI vehicle is assumed to be 20%, implying a fuel consumption rate of 5.2 L/100 km (equivalent to 1.71 MJ/km). According to Ref. [31], the H/C ratios of gasoline and naphtha comparable to the fuels defined in this study are 1.82 and 2.18, respectively. Accordingly, the emission factors are calculated to be 71.7 g $CO_{2,e}$/MJ for conventional gasoline and 69.6 g $CO_{2,e}$/MJ for low-octane gasoline. These estimations are generally in line with the Environmental Protection Agency (EPA) estimations [50].

Table 2
Process energy consumptions and yield ratios of target products in the relevant refining units.

Refining unit	Process energy consumptions			Target product	Yield ratio (%)
	Process fuel (MJ/kg)	Electricity (Wh/kg)	Steam (g/kg)		
Atmospheric Distillation	0.385	6.57	32.9	Naphtha	7.6
Vacuum Distillation	0.231	2.19	32.9	Vacuum gas oil	27.5
Hydrotreator	0.770	14.60	43.8	Light naphtha	13.5
				Heavy naphtha	50.0
Hydrocracking	0.770	58.39	165.7	Heavy naphtha	30.0
Isomerization	1.540	7.30	–	Isomerized gasoline	98.0
Catalytic Reforming	2.310	21.90	99.3	Reforming gasoline	80.4

Table 3
Fuel consumption rates derived from the Saudi Aramco bench tests.

Fuel	RON	Compression ratio	Fuel consumption rate (g/Kw h)	Fuel savings (%)
Gasoline	93	12	287.64	–
Naphtha	62	12	222.06	22.8
Naphtha	66	12	235.02	18.3
Naphtha	68	12	245.07	14.8
Naphtha	68	13	221.20	23.1
Naphtha	68	14	213.43	25.8

3. Results and discussion

3.1. WtT phase results

Table 4 shows the energy consumption and GHG emissions from fuel production stages. These results are generally consistent with existing estimations [51]. For the fuel production stages, the energy consumptions of conventional gasoline and low-octane gasoline are 0.143 MJ/MJ and 0.077 MJ/MJ; GHG emissions are 11.6 g $CO_{2,e}$/MJ and 6.7 g $CO_{2,e}$/MJ, respectively. Compared with conventional gasoline, the energy consumption and GHG emissions of low-octane gasoline are reduced by 46.1% and 42.6%, respectively. The major reason behind the reductions is the removal of the isomerization and catalytic reforming units, which exhibit high energy consumption and GHG emissions.

With vehicle fuel consumption rate considered, the energy consumption and GHG emissions from the WtT phase are 0.31 MJ/km and 24.9 g $CO_{2,e}$/km for conventional gasoline, and 0.13 MJ/km and 11.4 g $CO_{2,e}$/km for low-octane gasoline, respectively. The WtT energy consumption and GHG emissions of low-octane gasoline are 56.9% and 54.1% lower than conventional gasoline. It can be found that the lower fuel consumption rate of the low-octane gasoline-GCI pathway contributes to further enhancing its energy and GHG advantages of the WtT phase.

3.2. TtW phase results

In the TtW phase, energy consumption and GHG emissions are mainly determined by vehicle fuel consumption rate. The energy consumption and GHG emissions are 2.14 MJ/km and 148.9 g $CO_{2,e}$/km for conventional gasoline-SI vehicles, and 1.71 MJ/km and 122.7 g $CO_{2,e}$/km for low-octane gasoline-GCI vehicles, respectively. Benefiting from the higher vehicle energy efficiency, the energy consumption and GHG emissions of low-octane gasoline-GCI vehicles are reduced by 20.0% and 17.6%, respectively.

3.3. Life cycle results

Fig. 3 illustrates the life cycle energy consumption and GHG emissions of the conventional gasoline-SI pathway and the low-octane gasoline-GCI pathway. The life cycle energy consumption and GHG emissions are 2.44 MJ/km and 173.8 g $CO_{2,e}$/km for the conventional gasoline-SI pathway, and 1.84 MJ/km and 134.2 g $CO_{2,e}$/km for the low-octane gasoline-GCI pathway. Compared with the conventional technology, low-octane gasoline-GCI pathway reduces energy consumption and GHG emissions by 24.6% and 22.8%, respectively.

To further observe the contributions from different phases, the reductions of energy consumption and GHG emissions from the WtT and TtW phases are compared, as Fig. 4 shows. According to the estimations, the WtT phase contributes to 29% of energy consumption reduction and 34% of GHG emissions reduction. The other 71% of energy consumption reduction and 66% of GHG emissions reduction are attributed to the TtW phase. The results indicate that both WtT and TtW phases play essential roles in realizing reductions in energy consumption and GHG emissions. Relatively, the TtW phase makes larger contributions.

3.4. Sensitivity analysis

The vehicle fuel consumption rate has a direct impact on energy consumption and GHG emissions of both the WtT and TtW phases. In the analysis above, the fuel saving rate of low-octane gasoline-GCI vehicles is assumed to be 20% compared with conventional vehicles. As reported by Saudi Aramco, this saving rate can range from 15% to 25% depending on the engine compression ratio and fuel used. This implies considerable uncertainties in the assumption. To address the uncertainty, a sensitivity analysis is conducted on the fuel saving rate. The life cycle energy consumption and GHG emissions reductions are examined under the fuel saving rates from 15% to 25%, as Fig. 5 shows. It turns out that when fuel saving rate reaches 25%, the life cycle energy consumption and GHG emissions reductions reach 29.3% (+4.7%) and 27.6% (+4.8%)

Table 4
Energy consumption and GHG emissions from the fuel production stages.

	Conventional gasoline		Low-octane gasoline	
	Energy consumption (MJ/MJ)	GHG emissions (g $CO_{2,e}$/MJ)	Energy consumption (MJ/MJ)	GHG emissions (g $CO_{2,e}$/MJ)
Crude oil extraction	0.018	1.51	0.018	1.51
Crude oil transportation	0.006	0.70	0.006	0.70
Refining	0.114	9.03	0.048	4.07
Product transportation	0.005	0.41	0.005	0.41
Total	**0.143**	**11.65**	**0.077**	**6.69**

The bold items are the total numbers, for which we want to attract the readers' attentions by using the bold type.

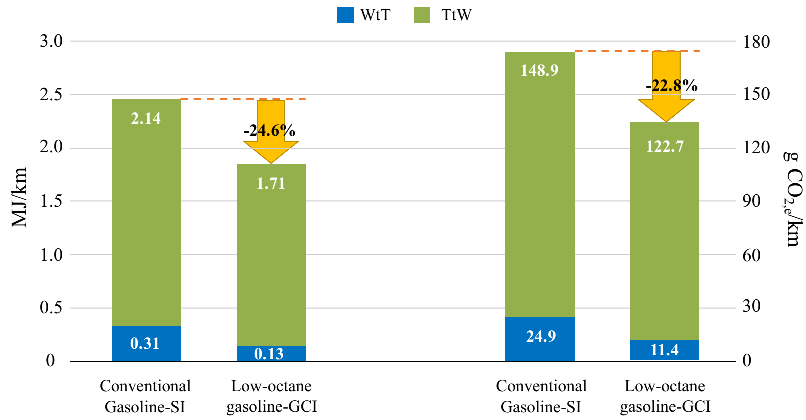

Fig. 3. Life cycle energy consumption and GHG emissions.

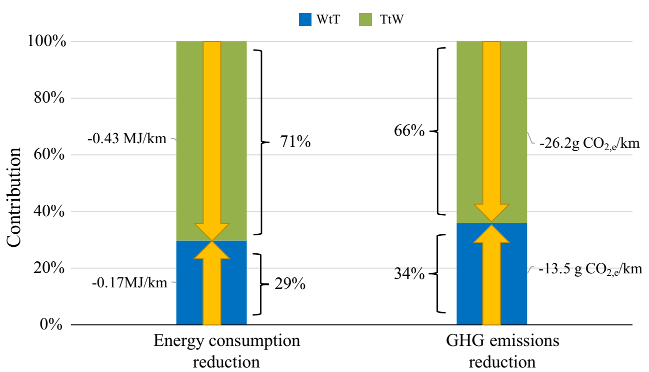

Fig. 4. The contributions of the WtT and TtW phases in reducing energy consumption and GHG emissions.

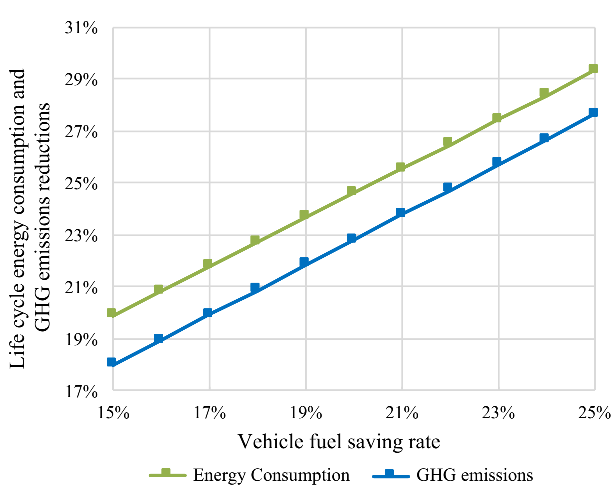

Fig. 5. The impact of vehicle fuel saving rate on life cycle energy consumption and GHG emissions reduction.

accordingly. Alternatively, when fuel saving rate falls to 15%, the life cycle reductions are 19.9% (−4.7%) and 18.0% (−4.8%). It can be found that the life cycle reductions in energy consumption and GHG emissions change in a similar extent with fuel saving rate.

The impacts of naphtha yield on life cycle energy consumption and GHG emissions are also examined. With the yield of naphtha from gas oil feedstock increasing from the current assumption of 30% to a potential higher level of 68% [41], the life cycle energy consumption and GHG emissions will be 2.46 MJ/km and 174.9 g $CO_{2,e}$/km for conventional gasoline-SI pathway, and 1.85 MJ/km and 134.8 g $CO_{2,e}$/km for low-octane gasoline-GCI pathway, respectively. The reductions in energy consumption and GHG emissions are 24.7% and 22.9%, which are quite similar to the original results. In other words, adjusting the yield structure of the refinery has little influences on the results.

4. Policy implications

As discussed above, the low-octane gasoline-GCI pathway offers the benefits of lower life cycle energy consumption and GHG emissions. This provides the basis for promoting the market penetration of such technologies. Under a global perspective, the availability of low-octane components is expected to increase as more crude is processed to meet increasing demand for middle distillates, such as diesel and jet fuel, used in commercial transport while the demand for gasoline stagnates or declines in the future. Low-octane gasoline components which would normally be further processed to make gasoline will be in surplus. This trend will become stronger if the octane number of the gasoline pool increases to enable more efficient SI engines or if alternatives like electric vehicles displace gasoline engines at a faster rate than now. Hence from a global perspective, low-octane gasoline will not need to be specially manufactured for GCI engines. On the contrary, GCI engines will enable low-octane gasoline components to be used effectively to improve the sustainability of refineries [52,53].

The cost of a GCI engine will be higher than a simple SI engine but will almost certainly be lower than an advanced diesel engine of comparable CO_2 footprint. The cost of SI engines seeking higher efficiency, enabled by such as downsizing and turbocharging, is also increasing rapidly. Moreover abnormal combustion such as knock, preignition/superknock are likely keep SI engine efficiencies below that achievable by CI engines such as diesel or GCI. Also there could be possibilities to keep costs down by making some compromises, e.g., by focusing on efficiency and cost rather than power [54].

Saving the isomerization and catalytic reforming processes contributes to reducing the facility and operation costs for the refineries. Especially, the gap in the cost at the refinery between low-octane gasoline needed for GCI and diesel or high-octane gasoline needed for efficient conventional engines will increase as the gap in global demand between middle distillates and gasoline increases. Refinery margins can be increased even while GCI fuel is sold at lower price than other fuels to customers.

From the infrastructure perspective, low-octane gasoline is highly compatible with existing storage, distribution and refueling infrastructures. It is possible that low-octane gasoline shares the existing infrastructure network with conventional gasoline. The transition cost from conventional gasoline-based fuel system to low-octane gasoline-based fuel system can be quite low. Besides, the drivers do not need to change the driving and refueling habits, which is a significant advantage over electric vehicles.

Despite the advantages analyzed above, there are also significant barriers to overcome. Although GCI technology contributes to reducing energy consumption and GHG emissions, it has the inherent problems of high NO_x and PM exhaust emissions. Under the more and more stringent emissions standards globally implemented, low-octane gasoline-GCI pathway cannot become a viable alternative to conventional gasoline pathway until the emissions issues are fully addressed. To address the emissions issues, advanced control technologies and combustion modes need to be further developed. Besides, as emerging alternative technologies, both low-octane gasoline and GCI engines lack the support of well-established technical codes and standards. For example, there is currently no accurate definition for low-octane gasoline. The physicochemical properties of low-octane gasoline, such as the RON and aromatics content, vary in different tests. The government needs to play an essential role in establishing relevant codes and standards. Intensive bench tests and field tests are needed to identify the most suitable fuel and engine technologies.

5. Conclusions

In this study, by establishing a process-based life cycle assessment model, the life cycle energy consumption and GHG emissions of the conventional gasoline-SI and low-octane gasoline-GCI pathways are estimated. It is found that compared with the conventional pathway, the low-octane gasoline-GCI pathway leads to a 24.6% reduction in energy consumption and a 22.8% reduction in GHG emissions. Both the removal of the isomerization and catalytic reforming units in the refinery and the higher energy efficiency in the vehicle use phase play substantial roles in achieving the reductions.

For the TtW analysis, difficulties arise because inventory data presented in most studies are incomplete. Data sources in some studies are not up to date. In the calculations, only process fuel, electricity and steam are taken into consideration to obtain the results for each refining unit. Other influencing factors, such as hydrogen production and catalyst production, are ignored to simplify the calculations. Moreover, the refinery configurations are different based on different crude oil or product requirements. It is difficult to determine a specific yield ratio for the low-octane gasoline. For the WtT phase, vehicle fuel consumption rates are estimated by referring to the bench tests results, rather than based on real-world data. Thus, there could be considerable uncertainties in the estimations. One possible further step is to incorporate more reliable real-world data into the analysis and calibrate the results.

Acknowledgements

This study is sponsored by the National Natural Science Foundation of China (71403142), Beijing Natural Science Foundation (9162008). The authors would like to thank the anonymous reviewers for their reviews and comments.

References

[1] Hao H, Geng Y, Sarkis J. Carbon footprint of global passenger cars: scenarios through 2050. Energy 2016;101:121–31.

[2] OICA. World motor vehicle in use. Organisation Internationale des Constructeurs d'Automobiles; 2015. Available from: http://www.oica.net/ [accessed March 2016].

[3] Hao H, Wang H, Yi R. Hybrid modeling of China's vehicle ownership and projection through 2050. Energy 2011;36(2):1351–61.

[4] IPCC. Climate change 2014: mitigation of climate change: transport. Intergovernmental Panel on Climate Change; 2014 [Chapter 8].

[5] IEA. CO_2 emissions from fuel combustion (2015 Edition). International Energy Agency; 2016. Available from: <http://www.iea.org/statistics/topics/CO2emissions/> [accessed March].

[6] Geng Y, Ma Z, Xue B, Ren W, Liu Z, Fujita T. Co-benefit evaluation for urban public transportation sector – a case of Shenyang, China. J Cleaner Prod 2013;58:82–91.

[7] Hao H, Liu Z, Zhao F, Li W, Hang W. Scenario analysis of energy consumption and greenhouse gas emissions from China's passenger vehicles. Energy 2015;91:151–9.

[8] Hao H, Geng Y, Li W, Guo B. Energy consumption and GHG emissions from China's freight transport sector: scenarios through 2050. Energy Policy 2015;85:94–101.

[9] Kalghatgi G. The outlook for fuels for internal combustion engines. Int Eng Res 2014;15(4):383–98.

[10] Hao H, Wang H, Song L, Li X, Ouyang M. Energy consumption and GHG emissions of GTL fuel by LCA: results from eight demonstration transit buses in Beijing. Appl Energy 2010;87:3212–7.

[11] Hao H, Geng Y, Hang W. GHG emissions from primary aluminum production in China: regional disparity and policy implications. Appl Energy 2016;166:264–72.

[12] Heywood J. Internal combustion engine fundamentals. New York: Mcgraw-hill; 1988.

[13] Kolodziej C, Kodavasal J, Ciatti S, Som S, Shidore N, Delhom J. Achieving stable engine operation of gasoline compression ignition using 87 AKI gasoline down to idle. SAE Technical Paper 2015-01-0832.

[14] Manente V, Johansson B, Canella W. Gasoline partially premixed combustion, the future of internal combustion engines? Int J Eng Res 2011;12(3):194–208.

[15] Kim K, Wang Z, Wang B, Shuai S, Yang H, Bae C. Load expansion of naphtha multiple premixed compression ignition (MPCI) and comparison with partially premixed compression ignition (PPCI) and conventional diesel combustion (CDC). Fuel 2014;136:1–9.

[16] Wang B, Wang Z, Shuai S, Xu H. Combustion and emission characteristics of multiple premixes compression ignition (MPCI) mode fueled with different low octane gasoline. Appl Energy 2015;61:769–76.

[17] Yang H, Shuai S, Fu H, Wang Z, Wang J, Zhou X. Combustion and emission characteristics of low-octane gasoline with partially premixed diffused compression iginition. J Automot Safety Energy 2011;2(4):330–7.

[18] Hanson R, Splitter D, Reitz R. Operating a heavy-duty direct injection compression-ignition engine with gasoline for low emissions. SAE Technical Paper 2009-01-1442.

[19] Sellnau M, Moore W, Sinnamon J, Hoyer K, Foster M, Husted H. GDCI multi-cylinder engine for high fuel efficiency and low emissions. SAE Int J Eng 2015-01-0834.

[20] Zhou Y, Johnson L, Wang M, Wang H, Hao H. Plug-in electric vehicle market penetration and incentives: a global review. Mitig Adapt Strat Glob Change 2015;20(5):777–95.

[21] Hao H, Wang H, Ouyang M. Fuel consumption and life cycle GHG emissions by China's on-road trucks: future trends through 2050 and evaluation of mitigation measures. Energy Policy 2012;43:244–51.

[22] Hao H, Wang H, Ouyang M. Fuel conservation and GHG (Greenhouse gas) emissions mitigation scenarios for China's passenger vehicle fleet. Energy 2011;36(11):6520–8.

[23] ICCT. Global passenger vehicle standards. International Council on Clean Transportation; 2015. Available from: <http://www.theicct.org/info-tools/global-passenger-vehicle-standards/> [accessed March 2016].

[24] Chang J, Viollet Y, Amer A, Kalghatgi G. Enabling high efficiency direct injection engine with naphtha fuel through partially premixed compression ignition combustion. SAE Technical Paper 2012-01-0677.

[25] Chang J, Kalghatgi G, Amer A, Adomeit P, Rohs H, Heuser B. Vehicle demonstration of naphtha fuel achieving both high efficiency and drivability with EURO6 engine-out NOx emission. SAE Int J Eng 2013;6(1):101–19.

[26] Viollet Y, Chang J, Kalghatgi G. Compression ratio and derived cetane number effects on gasoline compression ignition engine running with naphtha fuels. SAE Int J Fuels Lubricants 2014;7(2):412–26.

[27] Chang J, Viollet Y, Amer A, Kalghatgi G. Fuel economy potential of partially premixed compression ignition combustion with naphtha fuel. SAE Technical Paper 2013-01-2701.

[28] Zhou X. The low-octane gasoline without aromatics and compression ignition gasoline engine research report (internal report).

[29] Li W, Fu F, Ma L, Liu P, Li Z, Dai Y. A process-based model for estimating the well-to-tank cost of gasoline and diesel in China. Appl Energy 2013;102(2):718–25.

[30] Badra J, Elwardany A, Sim J, Viollet Y, Im H, Chang J. Effects of in-cylinder mixing on low octane gasoline compression ignition combustion. SAE Technical Paper 2016-01-0762.

[31] Morganti K, Alzubail A, Abdullah M, Viollet Y, Head R, Chang J, Kalghatgi G. Improving the efficiency of conventional spark-ignition engines using octane-on-demand combustion-part ii: vehicle studies and life cycle assessment. SAE Technical Paper 2016-01-0683.

[32] Yang H, Wang Z, Shuai S, Wang J, Xu H. Temporally and spatially distributed combustion in low-octane gasoline multiple premixed compression ignition mode. Appl Energy 2015;150:150–60.

[33] Wang M. The Greenhouse gases Regulated Emissions and Energy use in Transportation (GREET) model. Argonne National Laboratory; 2015. Available from: <https://greet.es.anl.gov/> [accessed March 2016].

[34] Jang J, Song H. Well-to-wheel analysis on greenhouse gas emission and energy use with petroleum-based fuels in Korea: gasoline and diesel. Int J Life Cycle Assess 2014;19(4):850–60.

[35] Furoholt E. Life cycle assessment of gasoline and diesel. Resour Conserv Recycl 1995;14:251–63.

[36] Wang M, Lee H, Molburg J. Allocation of energy use in petroleum refineries to petroleum products implications for life-cycle energy use and emission inventory of petroleum transportation fuels. Int J Life Cycle Assess 2004;9(1):34–44.

[37] Han J, Forman GS, Elgowainy A, Cai H, Wang M, DiVita V. A comparative assessment of resource efficiency in petroleum refining. Fuel 2015;157:292–8.

[38] Walls WD. Petroleum refining industry in China. Energy Policy 2010;38(5):2110–5.

[39] Xu C, Yang C. Petroleum Refinery Engineering. Petroleum Industry Press; 2009.

[40] Zhang Y. The process design of introducing light naphtha isomerization unit. Petrol Process Petrochem 2012;43(8):17–21.

[41] Xia Q. Hydrocracking technology and unit design for naphtha production. Petrol Process Petrochem 2015;46(6):17–20.

[42] Gary J, Handwerk G. Petroleum refining: technology and economics. CRC Press; 2001.

[43] EIA. Refinery capacity report. Energy Information Agency; 2015. Available from: <http://www.eia.gov/petroleum/refinerycapacity/> [accessed March 2016].

[44] Ou X, Zhang X, Chang S. Scenario analysis on alternative fuel/vehicle for China's future road transport: life-cycle energy demand and GHG emissions. Energy Policy 2010;38:3943–56.

[45] Ping Hou, Hongtao Wang, Zhang Hao, et al. Greenhouse gas emissions factors of Chinese power grids for organization and product carbon footprint. China Environ Sci 2012;32(6):961–7.

[46] SAC. General Principles for Calculation of the Comprehensive energy consumption (GB/T 2589-2008). Standardization Administration of China; 2008.

[47] Toyota Motor Corporation. Well-to-wheel analysis of greenhouse gas emission of automotive fuels in the Japanese context: well-to-tank report. 2004. <http://www.mizuho-ir.co.jp/english/knowledge/report/wtwghg041130.html>, accessed March 2016.

[48] Gao Y, Wang A, Gao C, Tao Y. Analyses of the energy consumption and emissions of crude oil transportation. J Mech Eng 2012;48(20):147–52.

[49] SAC. Fuel consumption limits for passenger cars (GB 19578-2014). Standardization Administration of China; 2014.

[50] EPA. EPA Emission Factors for Greenhouse Gas Inventories. <https://www.epa.gov/sites/production/files/2015-07/documents/emission-factors_2014.pdf>, accessed March 2016.

[51] Liu X, Long J, Zeng S, Xie Z. Research on CO_2 emission of oil refinery. Chem Ind Eng Prog 2011;30:809–15.

[52] Kalghatgi G, Gosling C, Wier M. The outlook for transport fuels: Part 1. Petrol Technol Quart 2016;Q1.

[53] Kalghatgi G, Gosling C, Wier M. The outlook for transport fuels: Part 2. Petrol Technol Quart 2016;Q2.

[54] Kalghatgi G. Petroleum-based fuels for transport. J Automot Safety Energy 2015;6(1):1–16.