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Lifecycle optimized ethanol-gasoline blends for turbocharged engines

Bo Zhang, S. Mani Sarathy *

King Abdullah University of Science and Technology, Clean Combustion Research Center, Thuwal, Saudi Arabia

HIGHLIGHTS

- Simulated lifecycle emission of different ethanol blended gasolines in different engine size.
- Sugarcane-based ethanol blending reduces lifecycle fuel emission while corn-based ethanol is not as effective.
- Increased engine compression ratio, turbocharging and downsizing reduce CO_2 emissions.
- An optimal lowest emitting ethanol blended fuel is formulated for use in future turbocharged engines.
- Greater cellulosic ethanol blending in gasoline yielding significant environmental and economic benefits.

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ABSTRACT

This study presents a lifecycle (well-to-wheel) analysis to determine the CO_2 emissions associated with ethanol blended gasoline in optimized turbocharged engines. This study provides a more accurate assessment on the best-achievable CO_2 emission of ethanol blended gasoline mixtures in future engines. The optimal fuel blend (lowest CO_2 emitting fuel) is identified. A range of gasoline fuels is studied, containing different ethanol volume percentages (E0–E40), research octane numbers (RON, 92–105), and octane sensitivities (8.5–15.5). Sugarcane-based and cellulosic ethanol-blended gasolines are shown to be effective in reducing lifecycle CO_2 emission, while corn-based ethanol is not as effective. A refinery simulation of production emission was utilized, and combined with vehicle fuel consumption modeling to determine the lifecycle CO_2 emissions associated with ethanol-blended gasoline in turbocharged engines. The critical parameters studied, and related to blended fuel lifecycle CO_2 emissions, are ethanol content, research octane number, and octane sensitivity. The lowest-emitting blended fuel had an ethanol content of 32 vol %, RON of 105, and octane sensitivity of 15.5; resulting in a CO_2 reduction of 7.1%, compared to the reference gasoline fuel and engine technology. The advantage of ethanol addition is greatest on a per unit basis at low concentrations. Finally, this study shows that engine-downsizing technology can yield an additional CO_2 reduction of up to 25.5% in a two-stage downsized turbocharged engine burning the optimum sugarcane-based fuel blend. The social cost savings in the USA, from the CO_2 reduction, is estimated to be as much as $187 billion/year.

1. Introduction

In the United States, ethanol is added to retail gasoline as a replacement for methyl tert-butyl ether (MTBE) and tetraethyllead (TEL), which have adverse health and environmental effects [1]. Since 1978, when ethanol was first introduced as a gasoline additive, the percentage of ethanol blending has gradually increased to today's mandate of 10%, with 830,000 bbls of biomass-based ethanol produced in 2013, exceeding domestic demand [2]. Ethanol blending reduces the demand for gasoline blendstock and benefits energy security [3,4]. With reduced domestic need, more gasoline blendstock could be directed towards Africa and Asia, where the demand rose by 20% and 6%, respectively, in 2014 [5].

Renewable fuel production is expected to increase to 36 billion gallons by 2022 [6]. Ethanol is expected to contribute most to the growth in renewable fuel demand [7]. Under the Energy Independence and Security Act, the waiver for E15 gasoline has already been partially granted to encourage the use of higher ethanol content fuel. The EIA estimates that an annual growth rate of 0.4% for domestic ethanol production can be expected until 2040 [2]. The production and application of ethanol in transportation fuel are expected to grow. The latest bioethanol production processes,

* Corresponding author at: Clean Combustion Research Center (CCRC), Al-Kindi Building (5) Room 4336, KAUST, Thuwal, Jeddah 23955-6900, Saudi Arabia.
E-mail address: mani.sarathy@kaust.edu.sa (S.M. Sarathy).

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technologies and applications have been reviewed to highlight its future potential [8,9].

The opinion towards blending ethanol in transportation fuel as a measure to reduce emission is split in literature. With the increasing demand of transportation ethanol, it is crucial that the effect on emission reduction is justified. Past studies have considered the direct emission offset by blending ethanol into gasoline or the effect of ethanol on engine performance [10–34]. The additional benefits from ethanol blending on enhancing fuel knock resistance, increasing engine efficiency and allowing engine downsizing have not been quantitatively assessed with emissions from upstream fuel processing. This study considers these aspects and establishes a comprehensive lifecycle model to assess the change in emission with full utilization of ethanol blended fuel in vehicles with turbocharged engines. The lifecycle emission of U.S. corn-based and Brazilian sugarcane-based ethanol are compared to that of gasoline to address the importance of the source of ethanol.

In the US, average regular grade gasoline has a minimum anti-knock index (AKI) of 87 with a research octane number (RON) of 91–92, while premium grade gasoline has an AKI of 91–93 and RON of 96–98 [18]. The AKI is the average of RON and motor octane number (MON). Existing gasoline engines have been designed to cope with the lowest octane-rated fuel on the market, which could have a RON as low as 89 [35]. In Europe, typical gasoline has a RON of 95 by law, which encourages the design of engines that operate at higher compression ratios [36]. Blending ethanol with gasoline can raise the octane number of the blendstock due to ethanol's inherent resistance to autoignition [37]. The RON of ethanol is 109 and MON is 90 [38]. The substantial differences from the octane quality of base gasoline make ethanol an ideal additive.

Higher combustion efficiency can be achieved with an ethanol-blended gasoline of higher octane number by increasing engine compression ratio [17,18,26,27,39–42]. Even under constant compression ratio, greater ethanol blending is shown to increase engine thermal efficiency, [40,43] with the highest efficiency identified for 40–50% ethanol [44]. A gain in part-load engine efficiency, and the induced charge cooling effect, also contribute to the improved engine efficiency with ethanol-blended gasoline [15,17,18,31,34,45–48]. With improved engine efficiency, ethanol blending also reduces fuel consumption on an energy basis, and thus, the regulated emission is reduced per-vehicle distance travelled [17,18,26,27,34,49]. Corn-based ethanol is blended into gasoline primarily in the United States and sugarcane-based ethanol is used in Brazil.

The lifecycle environmental impact associated with production and processing of bioethanol has been widely studied. The amount of atmospheric CO_2 captured and stored in the biomass is counted towards its biogenic credit, which partially offsets emission in the production and transportation of bioethanol. Proponent studies advocate for bioethanol as a fuel to reduce greenhouse gas (GHG) emission [22,25,50–55]; while other studies argue that the cost of bioethanol production outweighs its benefit [56–60]. This discrepancy regarding the net CO_2 emission of ethanol-blended gasoline stimulates the debate around higher ethanol-content fuels. The use of ethanol fuel has also stimulated discussion concerning the increased aldehyde emissions [61–64].

In the 2009 Climate Action Plan, the U.S. targeted a national greenhouse gas (GHG), reduction of 17% by the year 2020 [65]. In 2013, GHG emission in the U.S. was 6673 million metric tons of CO_2 equivalent, 27% of which was contributed by the transportation sector [66]. Light-duty vehicles (LDV) are responsible for the majority of gasoline consumption in the transportation sector, GHG benefits from bioethanol may offer an opportunity to reduce global CO_2 emission. A complete lifecycle study of ethanol-blended gasoline must be performed to confirm its benefit in reducing GHG emission. Higher ethanol blending can reduce refinery crude oil use and CO_2 emission by 8% and 10%, respectively, with E30 gasoline of RON 100 [67]. A higher octane number in ethanol-blended gasoline enables new engine technologies to utilize the improved knock resistance for greater engine performance. Studies have shown that greater engine efficiency can be achieved by using a higher octane-rated fuel in existing spark-ignited (SI) engines, while further gains can be reached by increasing compression ratio (CR), turbocharging and engine downsizing [17,68–70].

Government regulation and standards are expected to facilitate the transition to a LDV fleet that operates on gasoline with higher knock resistance in high CR turbocharged engines. Ethanol blended fuel is appropriate for such engines. The U.S. EIA predicts that with increased fuel economy, emission from the transportation sector will decrease by 0.2% per year, despite increased travel and demand for larger vehicles [2]. The U.S. EPA [71] projects that average CO_2 emission for the LDV fleet will be reduced to 101 g/km by 2025.

Other alcohols such as butanol are also fuel additive candidates; however ethanol has the highest energy retaining efficiency by far (72%), and is the only option that is economically viable with current technology [72]. Niass et al. [73] showed that butanol blended gasoline exhibits similar enhancement to fuel RON, sensitivity and CO_2 emission. Irimescu [74] showed the reduction of fuel conversion efficiency with iso-butanol was due to incomplete fuel evaporation.

This study examines the effect of blending ethanol with gasoline and its lifecycle CO_2 emission, with a special focus on turbocharged engines. The possibility of reducing CO_2 emission with a higher ethanol content fuel is investigated. Refinery simulation and its production emission were combined with the modeling of vehicle fuel consumption to determine the emission associated with different stages of fuel production and utilization. This study considers the combined effect of RON and octane sensitivity (OS, OS = RON-MON) on improving knock resistance in ethanol blended gasoline. As discussed in more detail later, fuels with higher OS improve knock resistance and enable higher engine compression ratio, engine turbocharging and downsizing.

The study also simulates the optimal blending percentage of ethanol when considering various refinery scenarios to produce a target gasoline RON and OS. Among the fuels simulated, the gasoline specification with the lowest lifecycle CO_2 emission was sought for use in modern engines. The effect of the bioethanol source on gasoline lifecycle emission is examined, using sugarcane-and corn-based ethanol. Annual CO_2 saving and associated social cost savings are also estimated.

This study is the first of its kind to evaluate the effect of ethanol addition on fuel lifecycle CO_2 emission in turbocharged engines. Past studies have investigated the change in CO_2 emissions resulting from anti-knock improvement, engine modification, optimization of fuel blending and fuel processing. The effect of each individual improvement on overall CO_2 emissions has been investigated, but an integrative study is lacking. The impact of ethanol addition on CO_2 emission cannot be justified without a complete lifecycle analysis. This comprehensive study quantifies the CO_2 emissions associated with upstream and downstream gasoline processes, refinery optimization, biogenic credits and fuel-enhancement-enabled engine modifications. This integration improves upon past research that have only studied selected aspects. The findings from this study provide a more accurate estimation on the net impact of ethanol addition on CO_2 emissions. Experimental and simulation results from the literature for engine efficiency and emissions for ethanol-blended gasolines are compared to our results in order to benchmark our findings [10–34].

The findings from this study show different results on fuel emissions depending on the source of ethanol. The advantage of ethanol blending in gasoline to reduce CO_2 emission is identified