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Complex Infrastructure-Vehicle-Consumer Considerations for Enabling Increased Consumption of Fuel Ethanol

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Abstract

Despite the rapid growth of the U.S. biofuels industry over the last two decades, the United States is struggling to meet Renewable Fuel Standard (RFS2) targets. In addition to the challenge of producing biofuels at cost that is competitive with petroleum gasoline, an additional expense for ethanol emanates from enabling its consumption as the US fuel market encounters the E10 ‘blend wall’—the maximum blend acceptable for use in existing gasoline infrastructure and vehicles. Without 1) rapid technological innovation in drop-in biofuel production, 2) increased tolerance of ethanol blends in existing infrastructure and vehicle standards, or 3) revision of the RFS2 to become production-focused instead of consumption-focused, options for increasing the average blend beyond E10 must come from a) increased consumption of mid- to high-level ethanol-gasoline blends such as E30 or E85, and/or b) increased E15 consumption among operators of vehicles manufactured in 2001 or later. We highlight research, deployment, and policy considerations to improve national and global alternative fuel system energy and GHG efficiency, and evaluate economic and emissions trade-offs associated with technically feasible strategies to increase ethanol consumption.

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1. Introduction

Common gasoline sold in the contiguous United States now contains 10% ethanol by volume, referred to as E10, which is the maximum blend acceptable for use in existing gasoline infrastructure and vehicles. The economic, technical, and policy factors that limit consumption of ethanol-gasoline blends higher than E10 in the United States have been discussed in several studies [1–5]. Some researchers have estimated the nationwide costs [4–6] and embodied greenhouse gas (GHG) emissions [7] associated with...
manufacturing more flexible fuel vehicles (FFVs) and installing more ethanol fuel blend dispensers. Unlike hydrogen, natural gas, and electricity, which require entirely different infrastructure and vehicles to enable utilization as a transportation fuel, ethanol could be considered a semi-fungible (or semi-‘drop-in’) blendstock for gasoline, with both attractive and unattractive properties. Regional differences in fuel regulations, emissions policies, available blendstock properties, ethanol infrastructure availability, proportion of FFVs in the vehicle fleet, climate, air quality, and other issues affect the technical considerations, compliance costs, and internal and external values of blending ethanol into a given fuel supply. Nontechnical challenges to managing a transition to greater ethanol consumption stem from consumer knowledge gaps and investor uncertainty about the longevity of policies.

1.1. Goals and Scope

Previous work has highlighted the complex tensions between economic, safety, air quality, and energy efficiency goals associated with various fuel-technology pathways [8]. Improving entire system performance requires a nuanced understanding of technical, economic, policy, and behavioral objectives for optimizing deployment of new resources and management of existing resources. For ethanol (and other blendstocks and additives), the marginal impact that increasing the blend level has on performance of the finished product may be linear (e.g., sulfur emissions), may be positive or negative (e.g., local air quality [9]), or may be unnoticeable beyond a certain threshold (e.g., knocking) in a given fleet. We use the term ‘differentiable value’ to describe a positive or negative performance difference when incorporating an alternative fuel (ethanol) into the traditional petroleum gasoline refining, blending, distribution, and vehicle system (‘fuel system’), in terms of internalities (e.g., profit) or externalities (e.g., unregulated pollution). Example questions in Table 1 address information needed to optimize strategies for increasing total throughput of biofuels, with particular focus on increasing the effective infrastructure-vehicle ethanol blend wall above E10. An equation that sums these values into a net differentiable value per unit of fuel throughput (e.g., \( \Delta_1 + \Delta_2 + \Delta_3 + \ldots \)) may be useful for isolated locations and time periods, but may produce misleading results if informing long-term national or global fuel policy.

1.2. Relevance of Consumer Refueling Errands

Recently, the US DOE reported on the projected capital costs, vehicle penetration, and potential availability of alternative fuel stations, recognizing that data on behavior and infrastructure development trends are lacking [6]. Instead of ignoring dedicated refueling errands (as common flow interception models may imply), the researchers estimated station accessibility within a three-minute-drive-time of vehicles. While potential diesel car owners would evaluate trade-offs in price and availability of refueling stations before purchasing a vehicle [10], FFV operators have the option to buy the most convenient fuel (typically E10) or to seek out higher blends (available at fewer stations than E10) before each refueling purchase. Just as some consumers pay for premium (high-octane) gasoline even if not required for their vehicle [11], some consumers in the US, Brazil, and Sweden pay a premium for ethanol [12,13]. Similarly, some drivers travel several minutes out of their way for a specific brand or price of gasoline [14]. As pro-biofuel drivers may be more likely than fuel-agnostic drivers to seek out high-level ethanol blends, and the lower volumetric energy density of ethanol requires drivers to refuel more frequently, emissions from consumer-to-station errands should be included in life-cycle assessments [7]. If incorporated into the ‘effective substitution ratio’ of ethanol defined by Yan et al. [15], such ‘errand premiums’ could easily add a fuel economy penalty of 0.5% or more (e.g., 1 km roundtrip errand for every 200 km driven).
Table 1. Fuel System Performance Qualities, and Questions to Determine the Differentiable Value of Fuel Blendstocks or Additives

<table>
<thead>
<tr>
<th>SYSTEM QUALITY</th>
<th>QUESTIONS TO CONSIDER</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. BLENDING PROPERTIES</td>
<td>Due to the unique physical or chemical properties of the biofuel (e.g., volatility, octane, aromatics, sulfur content), what is the differentiable value of the blendstock/additive to petroleum refiners and blenders in meeting finished fuel specifications (e.g., reduced crude refining costs, reduced need for additives)?</td>
</tr>
<tr>
<td>2. EASE OF DISTRIBUTION</td>
<td>Do unique fuel properties result in differentiable value to fuel storage, handling, transporting, and dispensing systems (e.g., fuel shelf life, infrastructure maintenance, safety and environmental measures, staff training)?</td>
</tr>
<tr>
<td>3. VEHICLE PERFORMANCE</td>
<td>Does the fuel offer differentiable value to drivers and fleet managers in vehicle performance (e.g., fuel economy, power/acceleration, reliability, maintenance frequency)?</td>
</tr>
<tr>
<td>4. ENVIRONMENTAL IMPACTS</td>
<td>Does the fuel offer differentiable value to the environment or public health (e.g., profile of vehicle exhaust emissions, leakage and evaporative losses from distribution and vehicle systems)?</td>
</tr>
<tr>
<td>5. CUSTOMER VALUES</td>
<td>If priced at vehicle-kilometer (v-km) parity, do some consumers perceive intangible differentiable value, expressing greater demand directly (e.g., paying a premium) or indirectly (e.g., driving farther to refuel)?</td>
</tr>
<tr>
<td>6. ECONOMIC RISK HEDGING</td>
<td>If reliability of supply or stability of input costs differ from petroleum products, do bulk fuel consumers perceive a differentiable value when entering contracts with suppliers (e.g., trading profits for reduced risks)?</td>
</tr>
<tr>
<td>7. PETROLEUM DISPLACEMENT</td>
<td>What is the (implied) differentiable value to a nation from producing or consuming the fuel domestically, in terms of trade, employment, tax revenue, and other political economic considerations?</td>
</tr>
</tbody>
</table>

2. Methodology

Although the concepts discussed above have all been previously addressed to varying degrees, a coordinated effort to model these impacts has not yet been reported. Assuming the volume and location of production is stable, we evaluate embodied costs and GHG emissions associated with producer-to-consumer fuel transportation logistics, infrastructure renewal, and vehicle replacements under hypothetical ethanol demand expansion strategies. We present simplified trade-off scenarios, to provide insights on the significance of fuel storage, transportation, dispensing infrastructure, and refueling activities in the overall GHG footprint of ethanol, with insights applicable to other alternative liquid fuels. We use previously reported GHG emission factors to estimate the GHG trade-offs and break-even distance involved in transporting ethanol far distances to areas with a high density of FFVs. Table 22 in the Appendix presents GHG break-even distances if ethanol marketers have the option to sell to local consumers that choose to drive an additional ’premium errand’ distance to refuel with E85 versus distributing ethanol to distant markets without a ’premium errand’ distance (neglecting differences in embodied emissions from pump station construction and utilization). Given the ’chicken and egg’ problem associated with ensuring high utilization of both FFVs and ethanol fuel blend dispensers, both of which have a turnover cycle of more than a decade, our model enables us to evaluate trade-offs in building many low-utilization tanks for comparison to fewer tanks with higher utilization rates.

3. Results

Distribute to Consumer-dense Distant Markets or Concentrate (E85) Consumption near Producers?

By using emission factors from [7] to generate Figure 1a, it can be seen that fewer GHG emissions would occur by transporting ethanol an additional 1,000 km by rail or barge, if doing so reduces the average E85
refueling errand distance by 1 km. In another example without any difference in consumer refueling errand
distances, the GHG emissions associated with transporting ethanol through a (hypothetical) pipeline from
Iowa to New Jersey (1,800 km), then shipping it to the Netherlands (6,500 km) by 25 kDWT tanker, would
be equivalent to the average multi-modal emissions for distributing ethanol in the United States (i.e., just
over 2 g CO$_2$–e/MJ from 1,409 km [7]). Emissions associated with shipping ethanol by barge from St.
Louis to New Orleans (2,300 km), then by small tanker to Santos, Brazil (9,700 km), would be
approximately double this amount.

Distribute to Unsaturated Distance Markets or Build Low-throughput E85 Dispensers Locally?

Fuel tanks and dispensers in rural parts of the Midwest tend to be utilized less than those in dense urban
areas. If embodied emissions are presented per fill-empty cycle (Figure 1b), delivery vehicles (trucks,
railcars, and barges) have greater emissions than storage tanks, though vehicle tanks are designed for more
frequent cycling than storage tanks. If addressing the question, “should we build a new E85 tank and
dispenser nearby, or ship ethanol 1,000 km to the closest unsaturated market?,” using Figures 1a and 1b,
we find that building a dispenser is preferable if it will cycle more than 20 times in its lifespan if truck is
the only mode available, but would need to cycle over 100 times if tanker, barge, rail, or pipeline are
available.

Trade-offs and Risks: Expanding the Blend Wall, Concentrating E85, and Other Options:

Capital costs for new liquid fuel stations may add $0.12/gallon to the levelized cost of fuel [6], translating
to $0.16/gallon-ethanol if the station is constructed to dispense E85 at the maximum ethanol content of 85%
by volume (vs. 10% in common gasoline). If the blend wall is raised to E15, achieving a net increase in
ethanol consumption of 0.78 gallons (as would result from consuming a single gallon of E85 instead of
0.72 gallons of E10, based on energy equivalence) would require approximately 15 gallons of E15 to be
purchased instead of 14.8 gallons of E10. The avoided E85-enabling capital costs would translate to
approximately $0.008/gallon-E15, which hypothetically could subsidize drivers to choose E15 over E10,
but only by approximately $5/vehicle/year (ignoring potential differences in maintenance or insurance
costs) unless the refueling convenience of E15 over E85 is also be monetized. Furthermore, the avoided
construction and avoided refueling errand premium could enable E15 to have lower emissions than E85 by
more than 1 g CO$_2$–e/MJ-ethanol.

Temporal dynamics in the vehicle fleet are ignored in this analysis. Assuming ethanol remains the
dominant fuel (and butanol or drop-in bio-gasoline remain uncommercial), ethanol fuel blend dispenser
stations may inevitably need to be built throughout the country if the common gasoline blend limit cannot
exceed E15. Alternatively, E85 stations may not be needed if the U.S. exports ethanol to countries without
blend wall concerns. Additionally, this analysis ignores environmental impacts of vehicle maintenance and
replacement, and air quality implications. Older (polluting) vehicles may be disproportionately affected by
ethanol, resulting in ‘early retirement.’ This phenomena may even benefit society, as government programs
such as ‘cash for clunkers’ were previously created to accelerate removal of old cars from the road [16].
Fig. 1. Contribution to the Life-cycle GHG Footprint of Liquid Fuel Products from a) Fuel Transportation Activities, as a function of transportation distance, and b) Embodied Emissions (Manufacturing, Construction, Maintenance), as a function of lifetime fill-empty cycles. Emission factors are obtained from [7]. Ethanol’s energy density, expressed as lower heating value (LHV), is 26.74 MJ/kg, so 100 kg/t translates to 3.74 g/MJ.

4. Conclusions and Discussion

This study presents an overview of a few interdependencies in the fuel system, modeled from a simple techno-economic perspective. Full appreciation for the technical risks, geographic heterogeneity, and temporal dynamics of the infrastructure and vehicle fleets, and potential transformation of biofuel producers towards drop-in fuels, requires more sophisticated modeling. In cases when ethanol could be shipped efficiently by pipeline or tanker (or rail or barge to a lesser extent) far from producers to regions that already have the market capacity to absorb more ethanol into their gasoline, significant emission savings may be achieved, potentially without increasing consumer errand distances or requiring new infrastructure. Although the RFS2 does not currently count exports towards volumetric mandates of obligated parties, doing so could reduce costs to U.S. fuel consumers, enable ethanol’s unique properties (e.g., octane, oxygenate) to benefit fuel refineries, consumers, and urban air quality abroad, and reduce global system-wide GHG emissions. Furthermore, delaying US investments in E85 fueling stations would allow future investors to recoup costs more quickly (when FFV penetration is higher), and could provide time for technological innovation in a) exploiting ethanol’s unique properties in existing or future engines, and/or b) reducing the overall need for ethanol fuel dispensers if drop-in gasoline becomes commercially viable.
Acknowledgements

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References

## Appendix A.

Table 2. Delivery Distances by Mode that Correspond with Equivalent Fuel Energy-normalized Emissions under Various Consumer Errand Distance Assumptions (assuming 10 gallons of ethanol per trip).†

<table>
<thead>
<tr>
<th></th>
<th>Life-cycle emission factor (g CO₂-equiv/t-km) from [3]†</th>
<th>Delivery or errand distance (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tanker (128 kDWT)</td>
<td>5.2</td>
<td>4,358 2,179 436</td>
</tr>
<tr>
<td>Pipe, Ethanol (25”, Northeast)</td>
<td>11</td>
<td>2,060 1,030 206</td>
</tr>
<tr>
<td>Tanker (37 kDWT)</td>
<td>12.4</td>
<td>1,828 914 183</td>
</tr>
<tr>
<td>Tanker (25 kDWT)</td>
<td>16.6</td>
<td>1,365 683 137</td>
</tr>
<tr>
<td>Unit Train (100-container)</td>
<td>25</td>
<td>907 453 91</td>
</tr>
<tr>
<td>Inland Tow (2-barge)</td>
<td>30.7</td>
<td>738 369 74</td>
</tr>
<tr>
<td>Truck, Long-Haul (24.3 t)</td>
<td>138</td>
<td>164 82 16</td>
</tr>
<tr>
<td>Truck, Short-Haul (24.3 t)</td>
<td>181</td>
<td>125 63 13</td>
</tr>
<tr>
<td>Vehicle (10 gal, premium refueling errand only‡)</td>
<td>22,660</td>
<td>1 0.5 0.1</td>
</tr>
</tbody>
</table>

Emissions associated with the distance specified, normalized to ethanol’s energy (CO₂-equiv/MJ)  
0.8 0.4 0.08

† Freight mode distances would increase by 4.3-times if consumers drove out of their way for E30, 1.3-times for E85, and would drop by 50% if consumers purchase 20-gallons per errand.
‡ Circuity factors have been ignored. Because railroads are more available in the United States than inland waterways, rail and barge emission factors diverge further to 31 and 49 g CO₂-equiv/t-km, respectively, if accounting for average route circuity [3].
§ This emission factor was estimated only from fuel consumed in the errand (i.e., not life-cycle emissions), which is assumed to result from a 20 mpgge vehicle purchasing 10 gallons of fuel [7].