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Historical perspective on the transition to alternative fuels to meet the greenhouse gas challenge

Perspectiva histórica sobre la transición a combustibles alternativos para afrontar el desafío de los GEI

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ABSTRACT: The worldwide consensus is that global climate change is being driven by humanity's release of fossil carbon into the atmosphere since the Industrial Revolution. Acting on the challenge of reducing fossil fuel and, particularly, petroleum consumption is our collective task. The need to act can seem daunting, given the enormous amount of petroleum that is consumed on a daily basis around the world, which has reached nearly 100 million barrels per day. However, humanity has seen major changes in our reliance on energy resources, in transportation and other sectors, over the last two centuries. Those changes have gotten us into this situation, but they provide more hope for our next transition as well. We can and must expand the adoption of low-carbon intensity renewable fuels, and we must do so in less than three decades, if we hope to limit the global temperature increase to less than 2°C. This paper provides a brief historical perspective on the use of transportation fuels and the transition that humanity must achieve and reports on a recent demonstration to support that transition.

RESUMEN: El consenso mundial es que el cambio climático global está siendo impulsado por la liberación de carbono fósil a la atmósfera por parte de la humanidad desde la revolución industrial. Actuar ante el desafío de reducir el consumo de combustibles fósiles y, en particular, de petróleo es nuestra tarea colectiva. La necesidad de actuar puede parecer abrumadora, dada la enorme cantidad de petróleo que se consume diariamente en todo el mundo, que ha alcanzado casi 100 millones de barriles diarios. Sin embargo, la humanidad ha visto cambios importantes en nuestra dependencia de los recursos energéticos, en el transporte y otros sectores, durante los últimos dos siglos. Esos cambios nos han sometido a esta situación, pero también brindan esperanza para nuestra próxima transición. Podemos y debemos ampliar la adopción de combustibles renovables con bajo contenido de carbono, y debemos hacerlo en menos de tres décadas, si esperamos limitar el aumento de la temperatura global a menos de 2°C. Este artículo proporciona una breve perspectiva histórica sobre el uso de combustibles para el transporte y la transición que la humanidad debe lograr e informa sobre una demostración reciente para apoyar esa transición.

1. Introduction

The worldwide consensus is that global climate change is being driven by humanity's release of fossil carbon into the atmosphere since the industrial revolution [1]. Acting on the challenge of reducing fossil fuel and, particularly, petroleum consumption is our collective task.

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But a question arises as to how best to meet this challenge, or put simply, "what is the fastest path to zero carbon?" Many governments are emphasizing a move to electrification of vehicles as a means of reducing greenhouse gas (GHG) emissions. As shown in Figure 1, the U.S. government "blueprint" for transportation decarbonization relies heavily on electrification, particularly for the light-duty sector. However, the blueprint includes diversity beyond just vehicle electrification. Regardless, these changes represent major shifts in how all aspects of transportation are fueled.

The U.S. Environmental Protection Agency (EPA) promulgates emissions standards both for criteria pollutants (e.g., carbon monoxide, unburned hydrocarbons, particulate matter, oxides of nitrogen) and for greenhouse gas emissions. The EPA outlines opportunities to lower the climate impact of transportation via three routes [3]:

- increasing the efficiency of vehicle technology
- changing how we travel and transport goods
- using lower-carbon fuels.

In this paper, we will focus on the third option and the challenge of making that transition.

2. The challenge of scale and lessons from the past

As reviewed by Boehman [4], the daunting challenge of addressing GHG emissions from transportation starts with the vast amount of fuel that is consumed on a daily basis. In 2020, the U.S. consumed 18.4 million barrels of petroleum per day. This translates to 32.2 quadrillion BTUs ("quads") of energy consumption from petroleum annually [5]. Just one "quad" is equivalent to 340,000 tank cars of crude oil which would stretch from Miami, Florida to Seattle, Washington, a distance of 3300 miles [6].

2.1 The current scale of petroleum and renewable fuel use

Furthermore, in 2021, according to the U.S. Energy Information Agency (EIA), the U.S. consumed [5]:

- 135 billion gallons of gasoline
- 46.8 billion gallons of distillate fuel (e.g., diesel fuel)
- 13.8 gallons of jet fuel

It is difficult to imagine a pathway to replacing and displacing these enormous volumes of petroleum derived fuels. Under the Renewable Fuels Standard (RFS), the U.S. has promoted the production and utilization of renewable fuels, providing a sliding scale of credits (referred to as "RINs", renewable identification numbers) depending on the renewable energy content of the fuel based upon a life cycle analysis of the fuel. Driven by the incentives provided under the RFS legislation, the latest production capacities reached the following levels as of January 2024:

- 2.07 billion gallons per year of biodiesel
- 17.83 billion gallons per year of fuel ethanol
- 3.86 billion gallons per year of renewable diesel and other biofuels

In this context, biodiesel refers to the mono-alkyl esters of animal fats and vegetable oils, and renewable diesel refers to hydrodeoxygenated animal fats and vegetable oils. Other biofuels include renewable heating oil, renewable jet fuel, renewable naphtha, renewable gasoline, and other biofuels and biointermediate products. In total, this represents 22 billion gallons of renewable fuels. This falls far short of the nearly 200 billion gallons of annual fuel consumption in the U.S., but it is a significant fraction that is growing rapidly. In the case of renewable diesel fuel (often referred to as "HVO"), production capacity in 2019 was 500 million gallons per year, but by the end of 2024, that capacity is expected to reach 5 billion gallons per year. That tenfold increase in capacity is a direct response to the "market pull" for renewable diesel fuel, because consumers are seeking drop-in replacements for diesel fuel that provide substantial decreases in fuel carbon intensity. This route to decarbonization and the motivation to pursue this route is covered in more detail in the next section, through a demonstration project pursued at the University of Michigan.

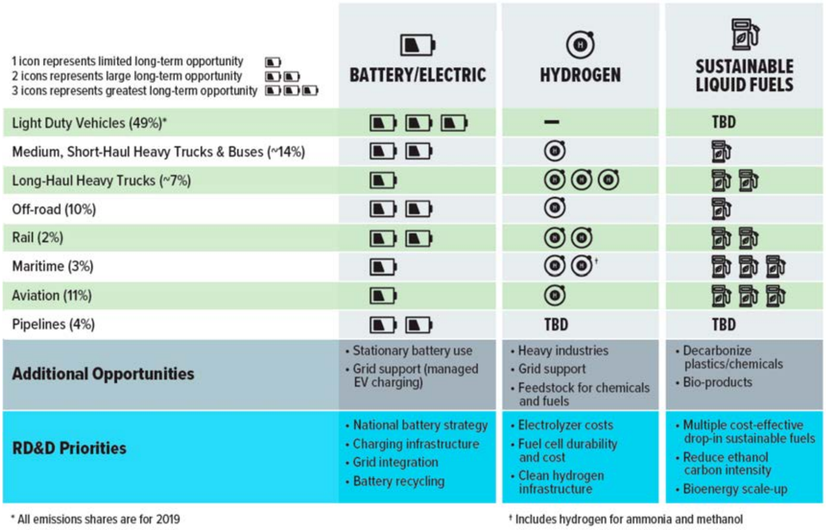
2.2 Lessons from the past

As described by the U.S. EPA, while the timeline for achieving decarbonization of transportation is aggressive to meet the targets for GHG emissions reductions, other major shifts in the transportation system have occurred over relatively short timescales [3]. The U.S. has a history of making large scale changes to the transportation system:

- Between 1900 and 1920, cars overtook horses as the primary mode of personal transportationl
- The entire U.S. interstate highway system was built in just 35 years
- Dramatic reductions in shipping costs were achieved by shifting to uniform containers for handling cargo; this change was accomplished in 30 years

The first point above is a dramatic example of a rapid shift in personal mobility, but only tells a portion of the story. The Otto cycle engine, which is used in most modern gasoline-fueled vehicles, was built upon the original internal combustion engine design of Lenoir, who in 1860 had built a non-compression engine that operated on gaseous fuel. These gaseous fuels included coal gas [7], Wood gas, or volatile hydrocarbons like turpentine [8]. As the petroleum industry developed in the late 1800's, and early 1900's, engines shifted toward operation on petroleum derived fuels.

From the perspective of the early 1900's, the future dominance of petroleum fuels as the energy source for transportation was not an obvious conclusion. In the 1800's, coal-fired, steam-powered locomotives, farm equipment, and ships proliferated and dominated transportation well into the 1900's. Clerk and Burls in a 1913 book that assessed the state of engine technologies at that time, drew what would seem an incredible conclusion today. Their assessment of coal and petroleum



1 icon represents limited long-term opportunity 🔋
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	🔋 BATTERY/ELECTRIC	◎ HYDROGEN	⛽ SUSTAINABLE LIQUID FUELS
Light Duty Vehicles (49%)*	🔋🔋🔋	–	TBD
Medium, Short-Haul Heavy Trucks & Buses (~14%)	🔋🔋	◎	⛽
Long-Haul Heavy Trucks (~7%)	🔋	◎◎◎	⛽⛽
Off-road (10%)	🔋🔋	◎	⛽
Rail (2%)	🔋🔋	◎◎	⛽⛽
Maritime (3%)	🔋	◎◎†	⛽⛽⛽
Aviation (11%)	🔋	◎	⛽⛽⛽
Pipelines (4%)	🔋🔋	TBD	TBD
Additional Opportunities	• Stationary battery use • Grid support (managed EV charging)	• Heavy industries • Grid support • Feedstock for chemicals and fuels	• Decarbonize plastics/chemicals • Bio-products
RD&D Priorities	• National battery strategy • Charging infrastructure • Grid integration • Battery recycling	• Electrolyzer costs • Fuel cell durability and cost • Clean hydrogen infrastructure	• Multiple cost-effective drop-in sustainable fuels • Reduce ethanol carbon intensity • Bioenergy scale-up

* All emissions shares are for 2019

† Includes hydrogen for ammonia and methanol

Figure 1 Summary of vehicle improvement strategies and technology solutions for different travel modes that are needed to reach a net-zero economy in 2050 [2]. (Note: "TBD" means "to be determined")

consumption for transportation was 237 million metric tons per year and 51.5 million metric tons per year, respectively. This led them to ask the rhetorical question: "Could oil entirely displace coal for motive purposes?" Their intriguing answer was:

"The world must mainly depend on coal for its motive power, whether it be used in steam or gas engines."

As pointed out by the U.S. EPA, by 1920, cars had overtaken horses as the primary mode of personal transportation. But for the larger transportation sector, renewable energy sources, such as wind for sailing vessels and biomass as feed for livestock that pulled vehicles, had already been displaced by coal and steam power in the early 1900's. The shift to petroleum and away from coal during the 1900's was itself a second rapid shift in the transportation system. One might argue that these rapid transitions were simply a reflection of the incredible acceleration of technological advances that have characterized the industrial age, but they nonetheless give hope that another major transition to decarbonize transportation while challenging, is not inconceivable.

2.3 Examples from the present

The University of Michigan campus transit system has 60 buses in service, 56 of which are diesel hybrid-electric and 4 are battery electric. In an effort to demonstrate that adoption of 100% renewable fuels in the University of Michigan transit system would provide a practical and viable pathway to significant GHG emissions reductions, a project was launched to both validate the operability of transit and waste management vehicles on 100% renewable fuel and quantify the GHG emissions reduction accounting for both the "well-to-tank" and "tank-to-wheel" impacts on carbon intensity of vehicle operation.

Over the course of three months, a campus refuse truck ran on a blend of 50% renewable diesel and 50% biodiesel (R50B50). Table 1 lists the specifications of the test vehicles. The goal of the trial was to attain a fuel economy value from an on-road trial to compare with other candidate fuels and thereby assess the GHG emissions reductions from the adoption of 100% renewable fuels. Table 2 shows a comparison of the well-to-tank carbon intensities and the volumetric energy densities of the fuels considered in this test and in this comparison. Biodiesel is less energy dense than conventional diesel. In this case, R50B50 is 13% less energetic per gallon when compared with conventional diesel, and 10.5% less energetic when compared to B20, the fuel which is used during the summer months. Assuming there are no system effects a similar decrease in fuel economy (miles per gallon of fuel) would be expected. Table 3 provides fuel properties from the certificates of analysis for the neat renewable fuels, provided by Renewable Energy Group, biodiesel and renewable hydrocarbon diesel.

Despite the lower energy density of both renewable fuels, the much lower carbon intensity (CI) of the renewable fuel was anticipated to lead to dramatic and immediate GHG savings over the course of the trial, even if we were to see a substantial loss in relative fuel economy.

To start the fuel trial, a pre-blended mixture of R80B20 was pumped into a 500gal tank used to refuel the refuse truck, as shown in Figure 2. This would then be topped off by hand with B100 until the appropriate mixture (R50B50)

Table 1 Test vehicle specifications

	Refuse Truck (Truck #1525)	**Transit Buses (Vehicles 3015/3016)**
Make and Model	Autocar ACX64	Gillig Low Floor 40
Model Year	2018	2019
Engine	Cummins L9, 8.9 liters	Cummins L9, 8.9 liters
Engine Peak Power (kW)	261	209
Gross Vehicle Weight (kg)	37455	18000

Table 2 Well-to-Tank carbon intensity and energy density of relevant fuels and mixtures

Fuels	**Carbon Intensity** (gCO_2/MJ)	**Energy Density** (MJ/gal)
Diesel	100	147.6
B5	96.25	146.6
B20	85	143.5
R50B50	27	128.4
R80B20	28.2	129.2

Table 3 Properties of the renewable fuels used in this study

Biodiesel: Property	**ASTM Method**	**Units**	**Value**
Cloud point	D2500	°C	-1
Flash point (closed cup)	D93	°C	172.5
Kinematic viscosity at 40°C	D445	mm^2/sec	4.057
Distillation at 90% recovered	D1160	°C	350
Cetane number	D613	not applicable	48
Renewable diesel: property	**ASTM Method**	**Units**	**Value**
Cloud point	D577	°C	-12
Flash point (closed cup)	D93A	°C	77
Kinematic viscosity at 40°C	D445	mm^2/sec	3.4
Distillation at 90% recovered	D86	°C	299
Cetane index	D4737, Procedure A	not applicable	95

was reached. This process was continued over the course of 3-months during which the refuse truck (UM vehicle #1525) traveled 4609.7 miles according to the truck's odometer. Over the course of the trial, the total fuel used was 1460 ± 30gal. This 2% uncertainty is present as a result of pumping the R80B20 into the tank. The pumps used had a stated uncertainty of 1% according to the fuel supplier, Chevron Renewable Energy Group (CREG), this is in addition to topping off the tank with B100 which adds another 1% uncertainty. Using the total miles traveled and the fuel consumed provided a robust value of the fuel economy. This mass balance results in a fuel economy of 3.15mpg ± 0.06mpg. The baseline value given for the refuse trucks' fuel economy was 2.95mpg. However, through historical data, this refuse truck was shown to have a fuel economy of 3.17mpg over a similar 3-month period. Accepting the measured value for fuel economy we see that there is a 0.4 % decrease in fuel economy from the B20 value when compared to the R50B50 value. This is not statistically significant and falls well within the range of experimental uncertainty. As a result, R50B50 and B20 have demonstrated roughly equivalent fuel economies for this vehicle over this time frame, despite the lower volumetric energy density as listed in Table 2. This can in part be explained by the lower sooting tendency of R50B50 when compared to B20. Because of this reduced soot emission, the vehicle could accumulate less particulate matter in its diesel particulate filter (DPF) and as a result, less back-pressure. This means that the engine does not need to work as hard when running off of R50B50.

Using the carbon intensities for these fuels, calculated and listed in Table 2, along with the calculated fuel economies, Figure 3 shows the calculated carbon dioxide equivalent emissions produced per mile (CO_2e g/mile basis) and those anticipated for the other candidate fuels, versus the diesel baseline. As shown in Figure 3, R50B50 has a significantly lower CO_2 produced per mile, stemming from its much lower carbon intensity. Predictably B20 is next best, with B5 and diesel being extremely similar. As shown R50B50 demonstrates a 75% decrease in CO_2 per mile compared with diesel. Compared with B20 we see a 70% decrease. This is substantial and immediate carbon savings that reduces the GHG emissions of the refuse vehicle. Table 4 provides quantified reductions in CO_2 based on the well-to-wheel basis that are shown graphically in Figure 3.

Table 4 Carbon Reductions in Comparison to Relevant Fuels and Mixtures

Refuse truck fuel	Total CO_2 produced (kg)	Total carbon savings (kg)	Percent carbon savings
R50B50	5064	–	–
B20	17083	12019	70.4
B5	20486	14422	75.3
Diesel	20833	15769	75.7

Figure 2 Test vehicle and refueling tank for 100% renewable fuel demonstration (R50B50) in a campus refuse truck, which show fuel economy parity despite the lower volumetric energy density of the renewable fuel. (photo credit: P. Chapman)

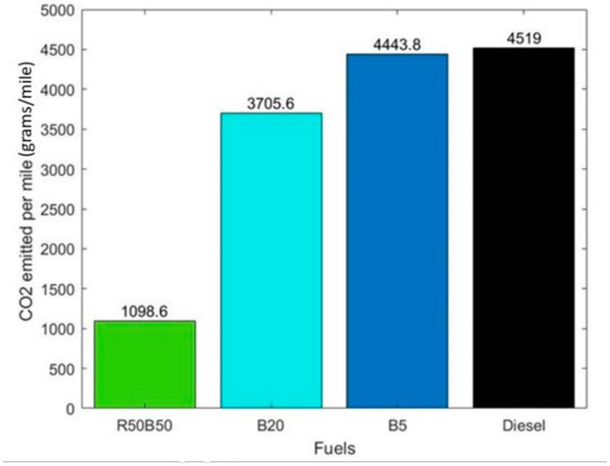

Figure 3 Comparison of greenhouse gas emissions (CO_2 equivalent emissions based on well-to-tank and tank-to-wheel considerations) for refuse vehicle operation

A similar trial occurred with two campus transit buses. However, the campus buses ran on R80B20 instead of R50B50. In this trial for diesel hybrid buses, the baseline fuel economy was 4.76 mpg. The fuel economy in the trial on R80B20 renewable fuel blend was 4.78 mpg, which suggests fuel economy parity. However, there was a misfuelling during the renewable fuel trial which created a confounding factor. The buses were refueled on the baseline B20 fuel during the trial as opposed to R80B20. The analyses of the fuel economy during the R80B20 trials account for this confounding variable by removing miles traveled under B20 from the R80B20 trial. Fuel economy parity was observed during the transit bus trial over this time frame, despite the lower volumetric energy density of the R80B20 blend, as listed in Table 2.

As with the refuse truck study on R50B50, Figure 4 shows that the R80B20 transit vehicle trial led to substantial CO_2e reductions. Figure 4 shows the CO_2 produced per mile during the bus trial for candidate fuels. R80B20 shows substantial GHG emission savings. Compared to B20 we see a 69% decrease, B5 shows a 74% decrease and diesel shows a 75% decrease. Additionally, no performance issues were reported during the trial duration.

Overall, both trials suggest that a switch to blends of renewable diesel and biodiesel would substantially and immediately reduce GHG emissions in both the refuse truck and the transit bus without needing any vehicle modification and without performance issues. There are gelling concerns for high biodiesel blends during colder months, but gelling was not observed during our trials, which took place before winter weather set in. The motivation to include biodiesel in the fuel blends arises from the cost differential between renewable diesel fuel and biodiesel fuel, as well as the availability of biodiesel. Due to the large and rapidly growing market demand for renewable diesel fuel, biodiesel is more readily available in the Midwest of the United States.

3. Conclusions

Acting on the challenge of reducing fossil fuel and, particularly petroleum, consumption is our collective task. Adoption of low carbon intensity renewable fuels must be

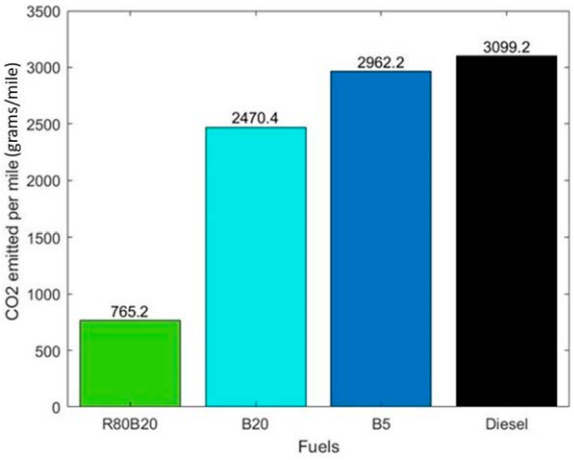

Figure 4 Comparison of greenhouse gas emissions (CO_2 equivalent emissions based on well-to-tank and tank-to-wheel considerations) for transit vehicle operation

a part of our strategy to achieving major GHG emissions reductions and must occur immediately, if we hope to limit the global temperature increase to less than 2°C. This study showed in two different types of vehicles, a refuse truck and diesel hybrid transit buses, that conversion to 100% renewable fuels led to around 75% reduction in carbon intensity. An intriguing outcome was that despite the lower volumetric energy content of the renewable fuel blends in comparison to the baseline fuels, the vehicles demonstrated roughly equal fuel economy on a miles per gallon basis. This outcome motivates a study of the mechanisms by which this fuel economy parity arose, which may derive from a reduced burden of flow resistance through the diesel particulate filter due to the lower sooting tendency of the renewable fuels. Verifying that hypothesis would provide additional motivation to make this transition to 100% renewable fuels where operation on drop-in renewable fuels meets the demands of the vehicle application.

Declaration of competing interest

We declare that we have no significant competing interests including financial or non-financial, professional, or personal interests interfering with the full and objective presentation of the work described in this manuscript.

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Author contributions

A. L. Boehman: Conceived and designed the discussion and analyses. P. Chapman: Collected the data and performed data analyses and prepared the discussion.

Data available statement

Data included in this paper can be provided by the corresponding author A. L. Boehman upon request.

References

[1] I. P. on Climate Change, *Global Warming of 1.5°C: An IPCC Special Report on the Impacts of Global Warming of 1.5°C Above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways*. Geneva, Switzerland: United Nations Environmental Program, October 2018. [Online]. Available: https://www.ipcc.ch/sr15/

[2] U. S. D. of Energy, "U.s. national blueprint for transportation decarbonization: A joint strategy to transform transportation," January 2023. [Online]. Available: https://tinyurl.com/4x2awfhk

[3] U. S. E. P. Agency, "Routes to lower greenhouse gas emissions transportation future," April 2024. [Online]. Available: https://tinyurl.com/42jxy5da

[4] A. L. Boehman, *Reciprocating Engines*. Cambridge, UK; New York, USA: Cambridge University Press, May 2023.

[5] U. E. I. Administration, "Annual energy outlook 2021," Washington, D.C., February 2021. [Online]. Available: https://www.eia.gov/outlooks/aeo/

[6] J. J. Eberhardt, "Fuels of the future for cars and trucks," in *Proceedings of the 2002 Diesel Engine Emissions Reduction (DEER) Workshop*, San Diego, California, August 2002. [Online]. Available: https://tinyurl.com/37kdpnj9

[7] D. Clerk and G. A. Burls, *The Gas, Petrol and Oil Engine: A Complete Treatise on the Internal Combustion Engine*. New York: John Wiley and Sons, September 1913.

[8] H. H. Schobert, *Energy and Society: An Introduction*, 2nd ed. New York: Taylor and Francis, June 2014.