Transportation Deep Decarbonization Initiative Synthesis

Options and Strategies Identified by a Roundtable of Experts from Industry, Academia, and Environmental Advocacy

Judi Greenwald, Principal, Greenwald Consulting
Jonathan Lewis, Director, CATF Transportation Decarbonization Program

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TASK FORCE

Table of Contents

1 **Introduction** 3

2 **Overview & Key Insights** 4

3 **Efficiency** 9

4 **Role of Consumer** 11

5 **Travel Behavior, Automated Vehicles, Transit, and Ride-hailing** 13

6 **Fuels & Energy Carriers** 17

7 **Integrated Engine, Fuel and Vehicle Potential Greenhouse Gas (GHG) Reduction and Cost** 22

8 **Freight** 26

9 **Aviation** 30

10 **Infrastructure** 32

Appx 1 List of Participants 35

Appx 2 Net-Zero-Carbon Fuels and Energy Carriers for Ground Transportation 36

Appx 3 Net-Zero-Carbon Fuels and Energy Carriers for Aviation 38

Appx 4 Overview of Vehicle and Engine Options and Issues for Aircraft 42

Clean Air Task Force would like to thank each of the experts who participated in the Transportation Deep Decarbonization Initiative (please see the full list of participants in Appendix 1), especially KG Duleep for his many contributions to the Initiative and this synthesis report.

SECTION 1

Introduction

From May through December 2020, Clean Air Task Force organized a Transportation Deep Decarbonization Initiative to explore this question:

> What are plausible options, scenarios and pathways for deep decarbonization of the transportation sector by 2050, how do they complement or compete with each other, and what can we do to maximize our chance of success?

About twenty-five researchers and thought leaders drafted background papers and virtually met via a ZOOM workshop on November 9th-11th under Chatham House Rules. **This synthesis paper summarizes the key insights from the papers, presentations, and workshop discussion, without attribution to any particular participants, and without inference that any specific insight represents a group consensus.**

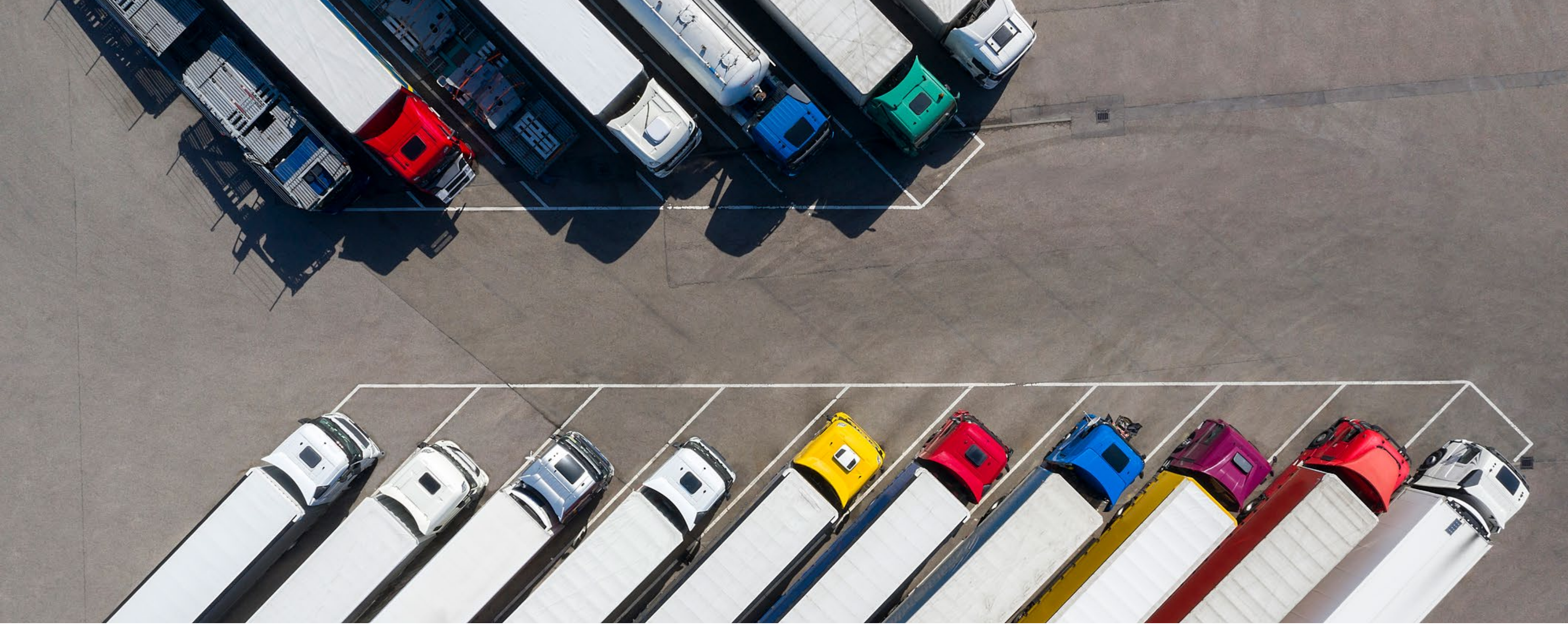
A comprehensive agenda on transportation deep decarbonization is timely, now that transportation has become the U.S. sector with the highest greenhouse gas (GHG) emissions. The Initiative drew on the extensive work already completed in this arena, while adding some new thinking. In particular, the participants strove to be realistic about the daunting challenges, but also focused on finding ways to overcome them. The deep decarbonization goal of the Initiative is to get as close as we can to a net-zero-carbon transportation sector by 2050 (at least in the United States). The participants are emphatically neither locked in nor opposed to any technological options; anything that can contribute meaningfully to decarbonization is on the table.

Although somewhat U.S.-oriented, the Initiative explored both domestic and international issues, as climate change is a global problem requiring global solutions. Although the Initiative is focused on transportation, participants explored some of the interactions between transportation and other sectors in achieving economy-wide decarbonization.

The Initiative explored both supply and demand with respect to all the transportation subsectors (moving people as well as goods through ground, air and marine transportation for long and short distances). Participants integrated expertise on a wide range of fuel, vehicle, travel, logistics, automation, service, and cross-cutting options by thinking through how the decarbonization pathways in specific subsectors could complement or complicate decarbonization pathways in other subsectors.

For each subsector, the participants explored:

1. Key current trends
2. Key technology and infrastructure options
3. Critical path issues
4. Path dependencies
5. Timing issues
6. Costs
7. Benefits
8. Key drivers and uncertainties with respect to:
    - Innovation
    - Markets/investment
    - Behavior/behavioral change
    - Public policy



SECTION 2

Overview of Key Insights

This synthesis paper identifies actions that can get as close as possible to a net-zero-carbon transportation sector by 2050 (at least in the U.S.). Actions include a mix of technology innovation, private investment and expenditures, behavioral change, and public policy.

2.1 Future Scenarios

The workshop started with a summary of some of the existing assessments of the rate and direction of transportation energy carrier[1] transition through mid-century. Leading business-as-usual projections include the International Energy Agency (IEA), World Energy Outlook (WEO), and the U.S. Energy Information Administration's (EIA's) International Energy Outlook (IEO). These assessments, based on existing policy and technology trends, describe a modest transition toward alternative fuels that could be characterized as quantitatively aggressive, but with associated emissions that are not low enough to keep planetary warming at or below 2 degrees Celsius. Developing countries play a large role in shaping the dimensions of future energy carrier demand. Under these reference case projections, transportation sector energy consumption in Organisation for Economic Co-operation and Development (OECD) countries is essentially flat through 2050 and grows significantly (75%) in non-OECD countries. Passenger vehicles are expected to be the largest transportation energy consuming subsector in both OECD and non-OECD countries; commercial trucking is the second largest and growing the fastest. Projected vehicle electricity use accounts for a small percentage (approximately 5%) of total transportation energy consumption in both OECD and non-OECD countries. Gasoline, diesel, and jet fuel are projected to account for over 90% of all fuel consumed over the entire 2019-2050 period in OECD countries, while natural gas plays a modest role in the non-OECD country transportation sector.

Not surprisingly, projections which limit (and eventually eliminate) transportation sector GHG emissions in ways that would be consistent with planetary warming of less than 2 degrees Celsius point to a very different mix of

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[1] An **energy carrier** is a substance (fuel) or sometimes a system that contains **energy** that can be later converted to other forms such as mechanical work or heat or to operate chemical or physical processes.

energy carriers and vehicle technologies. Recent modeling efforts in the U.S. context describe a near-zero-emitting 2050 transportation sector powered almost exclusively by net-zero-carbon electricity (including from renewable energy [RE], nuclear and fossil or biomass fuel with carbon capture generation sources) and hydrogen-based fuels (produced from RE and nuclear-powered electrolysis and from carbon-capture-equipped gas reformers that convert natural gas and gasified biomass into hydrogen).

Ultimately, transportation solutions for non-OECD countries (and the rest of the world, for that matter) must be affordable and attractive to consumers—e.g., they must be inherently cheap and convenient and/or must be required or incentivized by ambitious policy.

2.2 The solution set

Although the transportation sector is now dominated by one fuel – petroleum – and one type of engine – the internal combustion engine (ICE) – a diverse set of solutions is likely essential to achieve transportation deep decarbonization.

As elaborated in Section 3 on efficiency, pursuing energy efficiency makes sense in all transportation subsectors, reducing GHG emissions in the near and medium term, and reducing the need to produce alternative fuels or energy carriers. Continuous improvements in aircraft and marine efficiency are expected in any event from market pressures alone, but significant further efficiency improvements in ICEs for ground transportation seem unlikely without additional policy.

As elaborated in Section 7 on integrated engine, fuel, and vehicle potential GHG reduction and cost, pursuing battery electric vehicles (BEVs) is necessary, but not sufficient. Batteries are very promising for the light-duty vehicle (LDV) sector, but consumer acceptance issues may limit their market penetration. Hydrogen may be a better option for heavier vehicles, and hydrogen infrastructure may be needed in other sectors beyond transportation – i.e., to provide fuels for industry and seasonal storage for electricity. Carbon-neutral ammonia is a promising fuel for marine applications. Pursuing ammonia and hydrogen for heavy-duty transportation and non-transportation applications could have spillover benefits for LDVs.

Biofuels are currently the most ubiquitous non-petroleum transportation fuel globally and are more or less compatible with existing engines, but potential global sustainable supplies of biomass are limited. Among the transportation subsectors, aviation faces the toughest technical constraints on fuel switching; aircraft require fuels that are energy-dense enough, and engines that are efficient enough, to enable aircraft to take off, remain airborne, and land. From a societal perspective, prioritizing limited biofuel supplies for aviation use makes sense, although current policies and markets are directing biofuels to LDVs, necessitating a staged transition of the biofuel production industry to serving aviation, if society makes that choice. Shipping will likely fuel-shift (perhaps to ammonia) before aviation because, as compared to aviation, the marine sector (including vessels, fuels, and fueling infrastructure) is subject to fewer regulatory, safety, and technical restrictions.

A future decarbonized transportation system will likely require net-zero or nearly net-zero-carbon fuels. These include zero-carbon energy carriers such as hydrogen and electricity, and potentially net-zero-carbon liquids that are made from zero-carbon energy sources such as renewables, nuclear power, or fossil combustion with carbon capture and storage (CCS). They can also include hydrocarbons whose combustion emissions can be net-zero on a lifecycle basis, if the carbon is sourced from biomass (that captures carbon from the atmosphere as it grows) or from carbon captured directly from the atmosphere through engineered systems.

Synthetic net-zero-carbon fuels have the greatest technical potential as "drop-in" fuels using existing infrastructure, but currently have very high production cost (on the order of $5-15 per gallon of gasoline equivalent [GGE]), at least in the near to mid term. These synthetic fuel costs are very dependent on electricity price, and electricity prices in some projections are anticipated to come down significantly. Lower electricity prices are not likely to sufficiently bring costs down to below those of fossil fuels without additional carbon policy of some sort, but may bring costs down to below those of biofuels where there is less potential for feedstock cost reduction. Synthetic fuels and biofuel blends are the only alternatives to petroleum that can be used in existing vehicles and pipelines.

The role of automated vehicles (AVs) in climate mitigation is unclear (we don't even know whether they will lower or raise emissions since they could result in more driving) and could differ by subsector (e.g. passenger LDVs vs freight). Artificial-intelligence-based logistics and route optimization could be important and potentially easier to implement than AVs. For personal travel, the AVs' GHG benefits or impacts depend on how they interact with zero-emission vehicles (ZEVs), ride-hailing, and ridesharing; the extent to which they are fleet-owned (since fleet owners are more likely than individual vehicle owners to buy efficient vehicles and use them efficiently); and the extent to which blurring the lines between public and personal transportation can co-optimize both. Also, if consumers accept less performance for AVs, AVs could be more efficient and lower-emitting.

Behavioral shifts could make a huge difference, but the impacts are very uncertain. More behavioral research is needed, and there are new opportunities to learn from COVID-induced behavioral changes. COVID has had an enormous impact on behavior, showing what is possible, but it is unclear to what extent the behavioral changes will stick. Indications thus far are that substitution of videoconferencing for commuting and business travel will persist, at least to some extent, leading to large potential GHG reductions. However, many COVID-induced behavioral shifts could, if they persist, actually increase GHGs (e.g., reduced transit use, moving to less densely populated areas that require more driving). Ride-hailing fleets using ZEVs and/or encouraging ride-sharing could reduce GHG emissions substantially. Consumer behavior can also affect freight (e.g., whether goods are ordered online and delivered to homes or delivered to stores to be bought in-person, and whether demand for rush delivery precludes capacity and route optimization).

With respect to freight transportation, the three pillars of action are: (1) improving freight efficiency, (2) decarbonizing fuels, and (3) changing powertrains. In the long-run, changing powertrains would have the biggest impact. There are many near- and medium-term low-hanging-fruit opportunities, especially in vehicle efficiency and logistics. Major demand growth is projected for freight, primarily in developing countries. Costs are critical to this commercial activity. The freight sector is not monolithic. As elaborated in Section 8 on freight, different approaches will be required to decarbonize bulk goods vs. consumer goods, and short- vs. long-haul transportation. The type of goods moved by each transportation mode varies significantly, with rail and marine carrying most bulk commodities like crude, mineral ores, coal, etc., while aircraft and trucking are typically used for higher-value consumer goods.
In the near-term, BEVs and fuel cell vehicles (FCVs) are considerably more expensive than conventional and hybrid options across multiple heavy-duty vehicles. Long-term, fuel cell and electric vehicles are expected to become more competitive with diesel, although they will likely need policy support for some time. The overall strategy for the freight sector over time is likely to be continuous efficiency improvements in the short term, logistics re-organization and perhaps improved fuels in the medium term, and net-zero-carbon fuels and vehicles in the long term.

The infrastructure challenges of moving away from oil are daunting. The developed world already has ubiquitous electricity, but interconnection and vehicle charging infrastructure still require substantial additional investment. Hydrogen may require substantially more investment than electricity in the developed world, but has potential benefits compared to electricity for vehicles, especially for the medium- and heavy-duty subsector in terms of refueling time, range, and total cost of vehicle ownership. Hydrogen has a bigger “chicken and egg” infrastructure investment problem than electricity, but addressing that challenge might be worth it, particularly because hydrogen offers benefits to the industrial sector as a fuel and to the electricity sector as a seasonal energy storage medium. Ammonia infrastructure is challenging as well because it is a difficult substance to handle. Ammonia is least challenging for the marine sector, because of that sector’s dedicated refueling infrastructure and fuel storage options. It is relatively easy to build on the substantial existing upstream biofuels infrastructure for the light-duty vehicle subsector. The aviation system would be relatively easy to change over to drop-in biofuels because of its substantial dedicated infrastructure, although changes would be needed and the supply of sustainable, climate-beneficial biofuel may be inadequate to meet the demands of any transportation subsector, much less multiple subsectors. Carbon capture could enable continued use of at least some fossil fuel infrastructure, but it entails infrastructure challenges, too (e.g., CO_2 pipelines).

Natural gas could help transition to net-zero-carbon fuels in several ways. Natural gas infrastructure (e.g., pipelines and rights-of-way) could be upgraded or transformed and re-purposed as hydrogen infrastructure. Initially some hydrogen could be transported by mixing natural gas and hydrogen in existing natural gas pipelines. Hydrogen can also be made from natural gas through methane reforming, and near-zero and perhaps net-zero-hydrogen can be made by adding carbon capture, and minimizing methane leakage. Renewable natural gas (RNG) offers the potential of carbon-neutral (or in some cases, carbon-negative) energy, but supply is likely to be small relative to overall demand.

2.3 Policy

Public policies are a cornerstone of the response to a societal problem like reducing transportation GHG emissions. Because transportation deep decarbonization is an especially thorny problem, the question of which policies make sense is a hard one.

Why is transportation GHG policy especially difficult? First, there is no one-policy solution. Carbon pricing would help, but it cannot, by itself, achieve the fundamental changes in existing social and technical systems and is politically challenging to implement, at least in the United States. Second, the time constants for change are decades. Expected vehicle lifetimes are greater than 15 years for light-duty vehicles and greater than 25 years for aircraft;[2] across-the-board new vehicle designs take more than five years for light-duty vehicles and 10 years for aircraft; consumer acceptance of novel technologies takes many years; and essential infrastructure change can take decades. Third, the transformation must be made in an uncertain future, in which new and existing technologies will change, the timing and extent of market acceptance is uncertain, public attitudes and politics will change, and the world economy will change and respond to deep decarbonization. Fourth, climate risk obliges society to hurry. Some transportation decarbonization progress is being made, but the pace is not nearly fast enough.

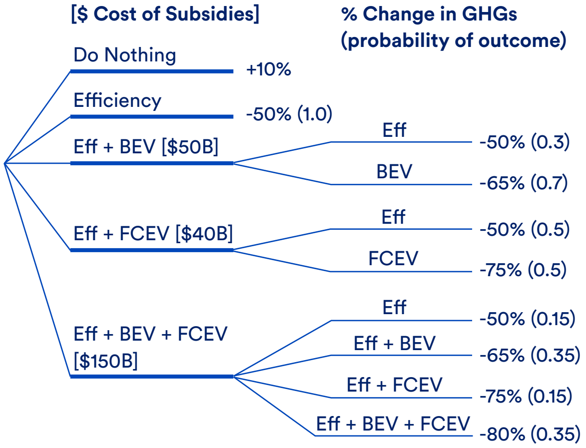
This means that policymakers must set clear goals and establish policies to achieve those goals that are both durable and adaptive. Historically, at least in the U.S. context, the most durable policies are those which are effective (in the sense that they achieve desired outcomes), cost-effective, efficient and equitable, and for which the compliance burden is not placed on the consumer. Building public support and addressing technologies' market acceptance are essential for policies to succeed. Adaptive policies require policymakers to thoroughly consider uncertainties, analyze alternative courses of action and their vulnerabilities, and emphasize robustness rather than optimality, so that the objectives can be achieved under a wide range of contingencies. Adaptive policies also require policymakers to continuously monitor successes, failures, threats and opportunities, and to adapt by changing policies and plans as future developments indicate. The best example of such a durable and adaptive policy in the United States is vehicle fuel economy standards, which have remained in place and have evolved over many decades with substantial public support.

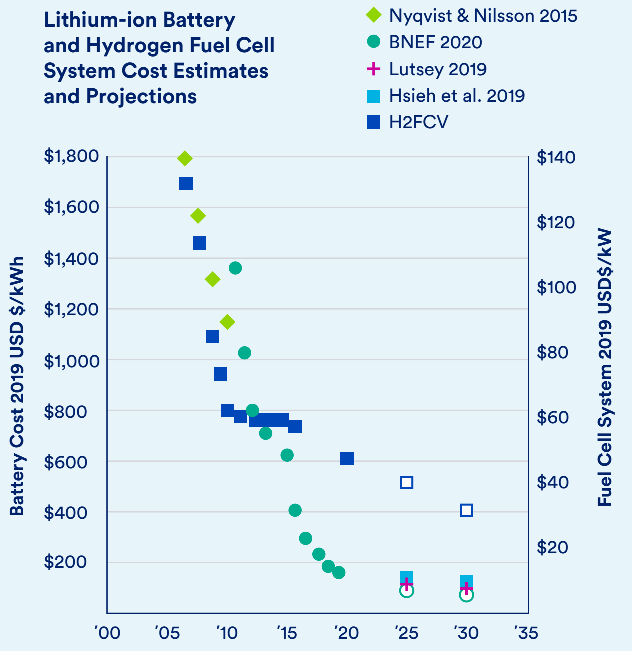
In each transportation subsector, there are experts and advocates who are sure they know what technological solution is best. Even if they are likely right, it still makes sense to pursue more than one option to ensure success. As shown below, even if one is optimistic about electric

Figure 1: Uncertain Technological Progress: Focus on BEV or Support both BEC and FCEV?

Source: NAS, 2013. Transitions to Alternative Vehicles and Fuels

(Efficiency case assumes 2X MPG standards & supporting pricing policies)




Lithium-ion Battery and Hydrogen Fuel Cell System Cost Estimates and Projections

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[2] Jiang, H., 2013. Key Findings on Airplane Economic Life, Boeing, accessed on 8/25/2020

vehicles, it still makes sense to continue to invest in energy efficiency and hydrogen vehicles, because the stakes and the technological uncertainties are so high. In the decision tree above, the hypothetical probabilities of success are shown in parentheses while the payoffs are percent reductions in light-duty vehicle GHG emissions based on NAS (2013).

As elaborated in Section 6 on fuels, the transportation sector is currently 90% oil-dependent, and there are multiple potential options for achieving a net-zero transportation sector by 2050. Thus, the best overall framework for the transportation sector is a performance-based, adaptive policy that lets various vehicle and fuel options compete as it moves us away from oil and/or reduces oil's GHG emissions over time.

A low-carbon fuel standard (LCFS) is such an overall framework for a suite of policies including vehicle emission standards. As implemented in California, an LCFS sets annual carbon intensity (CI) standards, or benchmarks, which reduce over time, for gasoline, diesel, and the fuels that replace them. CI is expressed in grams of carbon dioxide equivalent per megajoule of energy provided by that fuel. CI takes into account the GHG emissions associated with all of the steps of producing, transporting, and consuming a fuel—the complete lifecycle of that fuel. The LCFS lets the market determine which mix of fuels will be used to reach the program targets.[3]

Theoretically, other policy options, such as carbon pricing, could achieve a similar objective. Several workshop participants want to keep a carbon pricing option open, but robust carbon pricing has proved politically challenging to implement, at least in the United States. Thus, of the options identified, an LCFS, segueing to or nesting net-zero-carbon fuel standards (ZCFS) by 2050, appears to be the most viable and most adaptive overall framework for the transportation sector. To address the "chicken and egg" problem of matching vehicles and fuels over time, the fact that different vehicles and fuels may work better in different transportation subsectors, and the fact that we may need interim solutions on the way to achieving net-zero emissions, the LCFS/ZCFS framework should integrate with a mix of subsector strategies, and a mixture of near- and long-term goals. These include vehicle standards (fleetwide GHG/corporate average fuel economy [CAFE]), increasing zero-emission vehicle (ZEV) requirements or incentives for all vehicle types, infrastructure investments in the most promising options; public and private research, development, demonstration and deployment (RDD&D); and potentially government procurement commitments, carbon pricing, gasoline taxes, credit-based congestion pricing, and registration and purchase penalties (via "feebates", for example[4]) on very low-fuel-economy vehicles. Other jurisdictions offer more aggressive policy making examples for the U.S. federal government to consider (e.g., some U.S. cities and states, Sweden, the EU in general, and Singapore).

Building support for GHG-reducing transportation and fuels policies will be difficult and may result in policy outcomes that are sub-optimal but still net-beneficial. Because continued and rapid technological progress along with sustained public support for policies are necessary, it is not all about economic efficiency or the most cost-effective solution but rather about finding solutions that are practical and cost-effective. Commercial/heavy-duty transportation needs to be a leading focus of policy development, as it may pose the biggest transportation decarbonization challenge. IEA research indicates that transportation emissions do not get to net-zero without carbon removal technology; primarily because of residual emissions from commercial vehicles and the alternative fuel manufacturing processes. Decarbonizing vehicles, especially those used for long-distance transport, will not happen without supporting policies.

A key question under an adaptive framework is at what point does public policy narrow incentives and requirements to a specific technology or technology set? Another key question is how to finance investment in more than one option? Individual companies might pursue a suite of options (e.g., Toyota on hybrids, EVs and HFCVs) while other companies might bet on a single technology (e.g., Tesla on EVs). One approach for pursuing multiple long-term options in an adaptive way would be to encourage regional hubs and corridors for particular fuels, obtaining the benefits of learning-by-doing without setting the entire nation on a single path prematurely.

In general workshop participants agreed that the current pace of policy change is too slow. Policies need to keep all reasonably viable solutions alive while also providing a clear statement of direction, to allow firms an opportunity to plan and execute policy-aligned business strategies. Policymakers will need to be active in this space, collaborate with researchers, investors, and industry, and make tradeoffs between solving the climate problem rapidly, and bringing customers and the public along.

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[3] https://ww2.arb.ca.gov/sites/default/files/2020-09/basics-notes.pdf

[4] A feebate is a policy mechanism that charges a fee for low-efficiency vehicles and provides a rebate for high-efficiency vehicles.

SECTION 3

Efficiency

Over the last 40 years, efficiency improvements through technology upgrades have been the primary source of GHG reductions in the transportation sector. Efficiency improvements have proved to be usually cost-effective to the consumer and typically do not change (and may even enhance) vehicle attributes desired by consumers such as range, refueling time and frequency, and durability. Technologies like computer control, fuel injection, and greater combustion efficiency are also synergistic with non-GHG emissions controls. The technology upgrades also typically demand little or no change in vehicle support infrastructure, making them easy to adopt. Policies accelerating the introduction of efficiency technology have widespread public support across the political spectrum, and policies like fuel economy standards have been adopted by most OECD countries and many developing countries such as India and China.

Efficiency improvements (including hybridization[5]) should be a part of GHG reduction strategies going forward for several reasons. First, improving efficiency reduces the need for conventional or alternative fuels, whatever they may be. For example, more efficient battery and fuel cell-powered drivetrains will reduce transportation sector demand for electricity, both as an energy carrier in BEVs and as a feedstock for electrolytic hydrogen production, which in turn could lower the cost of building out sufficient zero-carbon power generation capacity.

Second, it is difficult to convince all vehicle owners to switch to electric vehicles and for the electric grid to decarbonize completely, so efficiency improvements provide a backup plan that would still achieve significant GHG reduction if the electric or hydrogen solution proves unworkable or incomplete by 2050. Third, very efficient vehicles in conjunction with low-carbon liquid fuels and possibly carbon capture and storage could conceivably offer a path to very large GHG reductions at lower cost than the fully electric path for at least some vehicle types. Fourth, if developed countries shift to BEVs or FCEVs, ICE-based vehicles could be exported

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[5] Combining electric and conventional fuel combustion power trains in one vehicle.

to developing countries, extending their lifetimes. That complication suggests, among other things, ICE efficiency will remain a key issue for decades at the global level. Finally, even in the developed world, ICE vehicles are expected to dominate new vehicle sales at least through 2030, and continued efficiency gains could buy time for other strategies by reducing emission loading in the near term.

LDV efficiency improvements have been studied extensively in most OECD countries in the context of setting new fuel economy or GHG emission standards. Although technology improvements beyond 2035 are more speculative, it appears that an approximately 50% fuel consumption decrease (or a doubling of fuel economy) relative to the 2020 average can be accomplished in the 2040+ time frame in most OECD countries with the use of gasoline-electric hybrid powertrains, at an estimated retail price increase of $5500 for a mid-size car or compact SUV. The auto industry is becoming more efficient and the costs of a "constant technology vehicle[6]" have been decreasing at about 0.6% per year for the last decade according to the U.S. Bureau of Labor Statistics. If these trends continue to 2050, it would imply a 16.5% (about $5000) reduction in conventional vehicle price, largely offsetting the price increase associated with new efficiency technology. Fuel savings provide substantial additional economic benefits. The European Union and Japan have already set vehicle CO_2 standards that would force near doubling of fuel economy over the next 15 years.

Unlike light-duty vehicles, medium- and heavy-duty freight trucks have more limited opportunity for improving efficiency with conventional technology, largely because the diesel engine that powers most trucks today is already quite efficient. In response to regulatory requirements, it is estimated that conventional freight truck efficiency could improve by 12-23% by 2035, depending on size and duty cycle, and potentially by an additional 5-10% by 2050 without any use of diesel-electric hybrids. According to analyses by NREL, hybridization could offer some additional benefit, but its cost effectiveness in long-haul trucking is poor and therefore unlikely to be adopted. The picture is better for medium-duty trucks used in urban duty cycles, but hybrids are still not very cost competitive as the benefits are relatively low compared to the cost. Hence, efficiency gains alone cannot provide enough reductions in this sector and fuel changes and/or electrification must play a bigger part.

Efficiency options for commercial aircraft also have significant potential to reduce GHG. Typically, new model aircraft provide large benefits in GHG emissions relative to the model they replace. An updated version of an existing design typically provides 12-15% fuel consumption reduction while a clean sheet of paper design with the latest engine and airframe technology could provide up to 25-30% reduction. Even higher reductions up to 40% may be possible with more unconventional designs (such as Boeing's Transonic Truss-Based Wing) that depart from the existing "tube-and-wing" architecture, albeit with increased technology risk. Electric aircraft are not expected to be feasible except for small, short-range urban air mobility vehicles. Hybrid electric–combustion engine aircraft could be feasible for short-range and regional routes (<300 miles), but their efficiency benefit may not be superior to next generation advanced design aircraft.

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[6] A hypothetical vehicle that does not change over time, for purposes of comparing costs over time.

SECTION 4

Role of Consumer

Conference participants noted that the role of the consumer in the LDV market had received little consideration in the discussion of decarbonization of personal transport. A number of automakers (original engine manufacturers or OEMs) and countries are making commitments to phasing out ICEs quite quickly. Many projections simply assume that the electric vehicle (EV) will displace most or all combustion engine vehicles in 15 to 30 years, but such a shift to EVs demands an en masse change of consumer behavior.

An examination of two innovations that appeared over a century ago and actually did change behavior forever- **Edison's light bulb** and the **Ford Model T** -help explain why consumer behavior undergoes massive shifts. These two inventions unseated incumbent technologies that had been dominant for centuries, and these inventions required (but also economically justified) new and costly infrastructure. The two technologies became much cheaper than the incumbent technology (the kerosene lamp and the horse carriage), achieving 30-60% cost reductions within a few years. The incumbent technology's cost fell in response to the new competition, but the costs of the new technology fell even faster.

Two other technology examples may also be instructive: the Dvorak keyboard and Betamax videotapes. They show that being slightly better than incumbent technology is not enough to gain traction in the market. New technologies have to be significantly better than the incumbent technology such that it's an obvious choice for all consumers. Otherwise the momentum behind the incumbent is just too large. Some would argue that from the consumer's perspective, EV's are more like Dvorak and Betamax with additional negative aspects than they are like a light bulb or Model T. If that's the case, policy will be essential to achieve widespread uptake of technology and the attendant societal carbon benefits.

Especially in LDV markets, non-GHG-related consumer preferences currently dominate, and could influence EV uptake in a range of ways; consumers value their time, so refueling time can be an important consideration. EVs currently take much longer to recharge than ICEs take to refuel; on the other hand, EV technology offers some consumers the convenience of at-home charging. Consumers value convenience, range, and dependability, so range anxiety (concern about the distance between refueling or recharging stations compared to the range of the vehicle) can be quite important; on the other hand, consumers may prefer the relatively clean and quiet performance and low maintenance requirements of EVs.

Different consumers have different preferences and different willingness to try new technologies. One technology is unlikely to deliver satisfaction across the board, and thus unlikely to spur true demand across the board. Thus a one-size-fits-all approach – such as assuming consumers will opt to shift to EVs in the absence of strong policy or broad OEM decisions to abandon ICEs - has significant risks (both for efficacy of decarbonization efforts and for automaker profitability).

According to one company, refueling issues and cost are the two most significant factors that lead to consumer rejection of EV purchase. EVs' advantages aren't enough to swing the market toward BEVs right now, but it's likely that EVs' market share will increase as cost goes down and range goes up. Car companies seem to think consumer preferences are changeable, based on internal investment patterns, and at least some investors seem to think so, too. The obstacles to change are indeed significant, but they are likely to diminish (BEVs will get cheaper, range anxiety will lessen as BEVs typically exceed 300-mile range and more charging stations are built).

While some recent analyses project that an EV with 200-250-mile range will achieve price parity with ICE vehicles this decade, these analyses typically assume that costs of ICE technology will continue unchanged. One analysis found that the Nissan LEAF cannot achieve cost parity with ICEs without subsidies, even with otherwise optimistic assumptions. Pricing and/or mandates can change that—but the delta to overcome is large. Hence, a rapid shift to EVs in 15 years without substantial market intervention appears to be unlikely at best. Ambitious policy will likely be essential to motivate a transition to electric vehicles.

The recent history of hybrid vehicle penetration illustrates the challenge of overcoming an incumbent advantage. The hybrid vehicle offers much better fuel economy than a conventional vehicle and does not compromise range or refueling ease, but is more expensive than the conventional vehicle (although the higher first cost is paid back by fuel savings in less than 5 years). Hybrids have been in the market for 20 years now; their market share climbed to about 3% of the U.S. market in 10 years, but stagnated at the 3 + 1% level since that time. The EV market share trend in its first ten years[7] has shown remarkable similarity to the market share trend for the hybrid, so there is a reasonable possibility that EV market shares may stagnate at low penetration levels in the future unless required or subsidized by the government, especially if gasoline prices decline as vehicles become fuel efficient globally. Automakers have enormous ability to shape consumer choices. Strong policy is likely needed to encourage automakers to use that ability to sell zero-emission vehicles.

The commercial truck market is thought to be one where truck operators who are more conscious of operating costs could shift even with modestly favorable economics, but typical operators also demand payback for new technology in 3 years or less, due to their aversion to technology risk. Analyses by NREL show that EVs will not be competitive even to 2040 for long-haul (>400 miles) trucks. However, EVs have modestly favorable economics relative to diesel for short-haul (<125 miles) urban delivery trucks that carry light, but volumetrically large loads. Even now, the reduction in total costs of ownership is less than the 30+ % historically required for a market-driven switch. If EV technology proves durable in commercial truck operation, this is a large market that could switch to electric propulsion, but will require a strong effort to overcome operator risk aversion. NREL and others think hydrogen fuel vehicles are a more competitive technology option in the long-haul market, particularly with respect to total cost of ownership.

Consumer demand is often overlooked when considering how to move toward a zero-emission future. The complex issue of consumer demand is often simplified into "purchase incentives" from governments and "more advertising" by OEMs. A major shift to EVs will require more understanding and consideration of how consumers can be motivated or required to make this shift in the absence of a large-market incentive.

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[7] Although small numbers of EVs with lead acid or nickel metal hydride batteries were sold prior to 2010, the introduction of the Li-Ion battery powered Nissan Leaf in 2011 is considered as the start of modern EV sales.

SECTION 5

Travel Behavior, Automated Vehicles, Ride-Hailing and Transit

Can behavioral change make a big difference in transportation demand, and therefore GHG emissions? Potentially yes, but it is difficult to get people to change their behavior. Household daily vehicle miles traveled (VMT), and consequently emissions, can vary by a factor of 2 between urban, accessible neighborhoods and suburban, car-dependent neighborhoods. In addition, safe infrastructure for low-speed travel (i.e., pedestrians, bicycles, and e-bikes) has significant potential to decarbonize much daily travel. For example, in the UK, car CO_2 emissions could be reduced 19% by replacing car travel with walking, bicycles, and e-bikes without any activity pattern or land use change.[8]

Recent COVID experience shows that big behavioral change leading to big changes in transportation demand is actually possible (at least temporarily), but the level of knowledge about behavior is considerably less than the level of knowledge about technologies and fuels. It is essential to conduct research as well as pilot programs on behavioral change.

What can be learned from recent experience with COVID pandemic-induced behavioral change? The pandemic has required most people to make large changes in their daily lives, but the extent to which any of these behaviors will stick is unclear. The COVID Future Survey project (covidfuture.org) has found that in comparison to pre-COVID behavior, respondents expect to increase working from home (from 28% pre-COVID to 45% post-COVID), to decrease business air travel by 43%, and to decrease personal air travel by 38%. They expect to walk a lot more and bike somewhat more than they used to. Some people may revert to pre-COVID norms in time, but the evidence strongly suggests people will settle into a new long-term normal that will be different

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[8] http://eprints.whiterose.ac.uk/147680/1/6-233-19_Philips.pdf

from the pre-COVID period. The pandemic provides an opportunity to study the impact on these behaviors as well as to encourage the ones that lead to emission reductions as opposed to emission increases. Preliminary data suggest that the U.S. could expect a long-term drop in car commuting miles on the order of 10-15% of pre-COVID car commuting miles (though induced demand might counteract some of these reductions), and that 15-30% of pre-COVID business air travelers expect a long-term reduction in business air trips.

People working from home can affect daily commuting in the short-term, and could affect where people choose to live in the long-term. If people choose to live in less dense places that are less amenable to transit and walking, that could offset the benefits of reduced daily commuting from working from home.

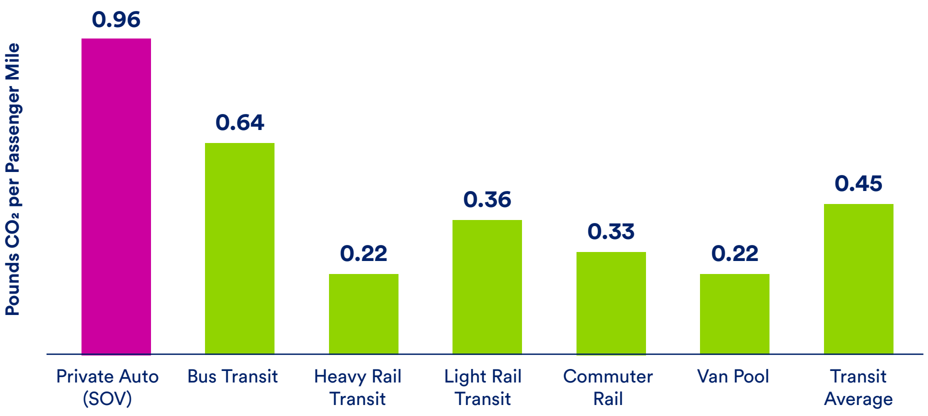
5.1 Transit

From a global perspective, transit use has and could have a very large impact on GHG emissions. As shown in the figure below, CO_2 emissions per passenger mile are significantly lower for transit than personal vehicle use. In addition to its direct decarbonization impacts, transit can indirectly reduce GHG emissions by encouraging urban density, which typically entails lower building energy use and increases the viability of sustainable options like walking, bicycling, and ridesharing as alternatives to single-occupancy vehicle use. However, in the United States, with its low population density and low capacity utilization of transit vehicles, transit constitutes a very low fraction of personal travel – about 1% of passenger miles.[9] Thus, even with a doubling or tripling of transit use, it would still constitute a small fraction. In the United States, improving vehicle emissions performance and ridesharing are likely to have a much greater impact on CO_2 emissions than increasing transit ridership alone.

Integrating public and private transportation could have a bigger impact on greenhouse gas emissions impact, by integrating multiple transportation modes and by solving the "first-mile/ last mile problem" through on-demand micro-transit. Even in areas with robust fixed route transit services, riders often have trouble completing the "first mile" of the trip from home to the rail station where there is a shortage of parking, or completing the "last mile" of their commute from the nearest transit stop to their workplace. In other cases, riders could complete their full commute on transit, but the journey would require so many transfers between infrequent local buses that transit becomes far less convenient than using a personal vehicle. To solve this problem, more than 200 cities across more than 25 countries have partnered with technology companies to provide dynamically

Figure 2: Estimated CO_2 Emissions per Passenger Mile for Transit and Private Autos

Source: See Appendix II for data sources and methodology



National averages show significant greenhouse gas emission savings from transit...

The average passenger car in the United States produces just under one pround of carbon dioxide per mile traveled.

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[9] (Bureau of Transportation Statistics, TSAR 2020, table 3-1)

routed, on-demand microtransit as a first- and last-mile solution, or to fill other geographic or temporal gaps in the existing transit system. While beyond the scope of this paper, it is also worth noting that a focus on improving transit can also help advance other important societal goals such as advancing equity and accessibility, reducing congestion, and increasing economic mobility.

5.2 Ride-hailing and Ride-sharing

Shifting away from personal vehicles could reduce GHG emissions. The advent of “mobility as a service (MaaS)” – for example, through ride-hailing – increased optimism that perhaps people might now be more willing to shed their cars. However, it is unclear what form MaaS solutions will take, and what their net transportation emissions impacts will be, especially in conjunction with automation (see below). Also, emerging mobility options will NOT soon make it economical for many Americans to shed their cars. Cars are expensive, except when compared to other transportation options. On a per-mile basis, and under current policies that fail to fully capture the externalities of vehicle trips, median operating (i.e., variable) costs for privately owned cars are quite low. If the average cost per mile for alternatives were $1.00, 10% of personally owned cars in the U.S. could be cost-effectively shed, but these cars represent only 2.4% of the miles traveled in personally owned cars today. In a world of technology-enhanced mobility options, traditional solutions for sustainable urban transport still apply – i.e., making driving more expensive (e.g., through fees); investing in sustainable alternatives like walking, biking, and transit; and encouraging ridesharing.

Fleet-owned vehicles would likely have lower per-vehicle-mile emissions than individually owned ones. Fleet owners are more cost-sensitive, more fully-value fuel savings, drive more and can therefore more quickly recoup the upfront cost of cleaner or more efficient vehicles through fuel savings. Fleetwide management of charging, trip, and vehicle capacity allows optimization of fleet size and functionality and reduces range anxiety with respect to electric vehicles.

Ridesharing – i.e., pooled rides that simultaneously serve multiple passengers, generally offered through ride-hailing companies – could potentially achieve a 30-43% reduction in VMT, emissions and costs – not only in urban but also in rural areas, where a large fraction of trips go to the same small number of destinations.[10]

However, prior to the COVID pandemic, the majority of hailed rides were single-passenger, with only one-fifth of ride-hailing customers opting for a truly shared ride (e.g., UberPOOL). In New York City pre-COVID, 67% of trips arranged by the ride-hailing/ ridesharing company Via were shared vs. 12.5% for Uber and 18.9% for Lyft.[11] Post-COVID, it is unclear whether people will be even more reluctant to share rides.[12]

5.3 Automated vehicles

Automated vehicles will likely affect future GHG emissions, but the direction of that effect depends on how their use interacts with personal mobility norms, vehicle technology and vehicle standards. Future AV scenarios range widely, from markedly higher to markedly lower GHG emissions.[13] On the one hand, many people can’t drive but could be driven, and many drivers would prefer to be driven and would be driven more than they would drive. On the other hand, ridesharing and using AVs to complement rather than compete with transit could limit VMT. Analysis assuming low ridesharing potential finds that vehicle automation could yield anywhere from a 60% decrease to a tripling of U.S. car and light truck fuel use by 2050.

Many expect that despite saving drivers’ time and reducing crash counts and severities, AVs will likely increase total VMT and thus increase congestion, at least for some time. This is due to the potential for non-drivers to travel independently, to empty vehicles repositioning themselves, and to more low-density land development at the periphery of regions. Preliminary results from Kockelman and Fagnant indicate that shared AVs can replace individually owned vehicles and achieve modest emission reductions, taking into account increasing

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[10] It’s up to us: Policies to improve climate outcomes from automated vehicles, Judith M. Greenwald, Alain Kornhauser, Energy Policy 127 (2019) 445–451

[11] Unlike other ride-hailing companies, Via picks up passengers at the closest street corner and deploys a routing algorithm that makes ridesharing relatively convenient and efficient. It also provides drivers with a financial incentive to do shared rides.

[12] Ibid

[13] Greenwald and Kornhauser, “It’s up to us: Policies to improve climate outcomes from automated vehicles, Energy Policy, March 2019

travel distance that is more than offset by fleet efficiency improvements and reduced embodied emissions.

AVs could also improve overall efficiency if consumers accept lower performance (e.g., slower acceleration). The extent of this benefit would depend on the powertrain technology; ICE-based powertrains would see a bigger benefit.

Policy makers could encourage AVs to be ZEVs, fleet ownership of AVs, ridesharing, and the integration of AV ride-hailing with public transit. This would blur the lines between public and private transit, making them complementary, improving overall system efficiency, and reducing GHG emissions. Much experience and many scenarios show ridehailing cannibalizing transit. However, some companies have demonstrated that ridesharing increases vehicle occupancy and that integrating ride-hailing as a last-mile/first-mile solution with transit can complement rather than cannibalize transit. Vehicle and fuel standards would reduce AV emissions as they would reduce all vehicle emissions.

For freight, automation similarly could increase or decrease GHG emissions. Highway platooning of automated trucks could increase efficiency for following trucks by 10-15% by reducing drag. Truck automation could allow trucks to travel during less congested times of day, reducing emissions. On the other hand, automation displacing drivers could reduce freight transport costs, reducing the incentive for efficiency and increasing emissions.

5.4 Travel Behavior and Goods Delivery

Consumer behavior can also affect goods delivery. During COVID, there has been a shift from shopping in physical stores, where consumers pick up their own goods, to online shopping, where goods are shipped directly to consumers, largely in line with prior upward online shopping trends. This increase in e-commerce has put more pressure on the last mile and is fragmenting flows. If these changes persist when the pandemic has passed and people pick up their old shopping habits again, the number of trips to get the same goods at home will have increased and utilization of vehicles will have decreased. Trade disruptions have created new supply chain dynamics (e.g., sudden shortages) that have reduced the willingness of firms to invest to make chains leaner, as this reduces reserve capacity and only makes them more vulnerable to disruptions. Manufacturers may therefore rather invest in overcapacity and excess stocks to prevent shortages in the future, decreasing vehicle utilization and increasing vehicle miles per tonne shipped.

COVID-related declines in commuting have relieved traffic congestion and thereby reduced the pressure on commercial carriers to invest in efficiency (e.g., investing in advanced routing and scheduling away from congestion). Once congestion returns, efficiency investment pressure will return.

Goods movement from warehouses to retail stores to consumers has shifted somewhat to warehouses sending goods directly to consumers. Consumer preferences for rapid delivery can encourage energy-inefficient goods movement. Incentives for consumers to choose lower-emitting goods transportation options (e.g., grouping orders to reduce the number of trips, allowing slower delivery times to increase capacity utilization of transport vehicles, creating pick-up points, subsidizing home lockers, etc.) could significantly reduce goods transportation and associated emissions.

SECTION 6

Fuels and Energy Carriers

6.1 Overview

A fully decarbonized transportation sector will require decarbonized energy carriers (i.e., liquid and gaseous fuels and electricity), or complete capture and subsequent utilization or sequestration of emitted CO_2. The Initiative focused on the range of possible energy carriers and their potential contributions to decarbonizing the transportation sector, the short- and long-term benefits of pursuing multiple energy carrier options, and the critical role that policies will need to play in the development, deployment, and acceptance of net-zero-carbon energy carriers.

The decarbonized energy carriers needed for the transportation sector are part of a complex, interdependent ecosystem that is also being shaped by changes to vehicles, energy infrastructure, mobility infrastructure, and behavior. Importantly, the rate at which the transportation sector transitions to less carbon-intensive energy carriers is strongly influenced by the rate at which different vehicle classes transition to new propulsion technologies.

The five main approaches for decarbonizing transportation sector energy carriers are:

- Electricity
- biofuels (both liquid and gaseous fuels derived from biogenic feedstocks)
- zero-carbon gaseous or liquid energy carriers (especially hydrogen and ammonia)
- synthetic hydrocarbons
- oil/gas paired with offsetting direct air capture

The five approaches can be—and likely need to be—pursued in parallel. Each subsector could be dominated by one approach, or could use multiple approaches. For example, electrification might play a major role in the decarbonization of light-duty passenger vehicles, ammonia might be used to eliminate GHG emissions from the marine shipping sector, and a combination of biofuels, synthetic hydrocarbons, and offsets from direct air capture might be used to achieve net-zero emissions in the aviation sector.

Several key technologies like carbon capture and renewable electricity generation are also likely to play a role in most or all of the approaches. Carbon capture, for example, could be used in zero-emissions electricity generation (e.g., gas-fueled turbines equipped with CCS), in bioenergy production (e.g., to eliminate direct emissions from biorefineries and, potentially, to achieve negative emissions), in net-zero-carbon fuel production (e.g., hydrogen-producing methane reformers equipped with CCS), and in the production of synthetic hydrocarbons (e.g., obtaining carbon feedstocks through direct air capture of CO_2). Similarly, renewable electricity generation could power electric vehicles, electrolytic hydrogen production systems, and the direct air capture machines that are central to the synthetic hydrocarbon and DAC-based offsetting approaches.

Attributes of each approach are summarized in the appendices (Appendix 1 for ground transportation and Appendix 2 for aviation). Timing and cost issues are major concerns across the board. Businesses want to see economic returns on investment as soon as possible, and consumer preferences tend to change slowly in the absence of clear and compelling benefits. Individually, each pathway has its strengths, but also carries a unique set of challenges. **Some of the highest-level challenges include:**

- "Non-drop-in fuels" (i.e., fuels other than gasoline, diesel, and certain biofuels and synthetic hydrocarbons that can be simply dropped into existing engines and infrastructure) face infrastructure and path-dependency challenges, as discussed more fully in Section 8 on infrastructure.
- Synthetic drop-in fuels with very low carbon intensity are technically feasible at large scale but are projected to be very costly over the foreseeable future (currently $10+ per gge).
- Biomass-derived drop-in fuels with very low lifecycle carbon intensity are supply constrained. Some biofuels are currently cost competitive, but these tend to be less environmentally friendly than "advanced" biofuels, which are not widely produced and will be significantly more expensive.
- Range anxiety is a key concern for BEVs; current EV batteries have smaller ranges than ICEs, and recharging infrastructure is far less ubiquitous than gas stations.
- Refueling time matters; currently BEV charging time is significantly longer than gasoline refueling time.
- Hydrogen is promising in terms of cost, refueling time, and range, but requires vast infrastructure buildout, and the cost of delivering hydrogen to a vehicle is a significant barrier.
- Carbon capture and storage (to lower lifecycle emissions) is still expensive.

6.2 Electricity

The cost of electricity significantly impacts overall costs associated with BEV ownership, but the future cost of electricity (particularly electricity generated in a rapidly decarbonizing power sector) was beyond the scope of the Initiative. As discussed in Section 11 on infrastructure, buildout of electricity charging infrastructure requires substantial investment. A key variable is whether charging can be "managed" so that vehicle owners are incentivized or required to charge "off-peak" when the demand for electricity for buildings and industry is relatively low, and spare capacity can be used to charge vehicles. If vehicle charging simply adds to electric system peaks, buildout will be much more expensive. Another issue is managing large power draws in specific locations.

The cost and performance of batteries will also keenly affect electricity's viability as an energy carrier. If battery costs decrease substantially, it would follow that BEVs could potentially be cheaper and thus more attractive to many current ICE buyers and that OEMs would be more motivated to meet that market demand. It is very hard to predict when that price crossover point will be achieved, although roughly $100/kwh battery is mentioned often as the threshold. As with other ZEVs, the higher the BEV cost, the more dependent we are on policy to motivate consumer interest and automakers to use their marketing ability to encourage consumers to shift to BEVs.

The cost and scarcity of lithium is often overstated; lithium is a small fraction of battery content, so even a 3x increase in Li prices would only increase battery costs (on a per KWh basis) by roughly 5%. The future supply of nickel and cobalt may be of greater concern. Battery recycling can offset some concerns about material demands, although there is a delay between batteries' initial manufacture, the return of materials, and their re-use. Existing battery recycling processes and supply chains are still small relative to the size of the automotive battery market, and focus on recovering high-value metals like nickel and cobalt. Methods are under development to capture both valuable metals and the embodied energy in battery cathode materials, potentially offering more opportunity to reduce future cost. Transportation of spent batteries to recycling facilities remains a key barrier to cost-effective battery recycling.

In the heavy-duty freight sector, experiments were done in Europe with catenary systems for long distance corridors. Studies suggest that the system is many times more energy efficient than a hydrogen alternative, the system would require minor overhauls of BEV systems, and the new overhead line infrastructure could be operated commercially with a break-even period of less than 15 years.[14]

6.3 Liquid fuels

Diesel, gasoline, jet fuel, marine oil, and other liquid fossil fuels are usually cheaper and have higher energy density than non-fossil liquid fuels, but full well-to-wheels life cycle GHG analysis needs to be taken into account. Several options could be pursued, individually or in conjunction, to reduce or offset the emissions from the use of fossil liquid fuels in the transportation sector. One option, currently pursued to varying degrees by European automotive manufacturers, is to increase the fuels' octane ratings. Higher octane ratings in the U.S. could allow the introduction of more efficient engines. One way to do that is to increase the amount of ethanol that is blended into gasoline, but care must be taken to ensure the additional ethanol has a lifecycle carbon intensity that is lower than that of ethanol made from conventional feedstocks like corn starch.

Another option is on-board carbon capture systems, in which the CO_2 emitted by a petroleum-burning vehicle is captured and stored in the vehicle (possibly in the fuel tank, as fuel is used and space becomes available). At least one firm has been working for a decade on this technology and has achieved a 40% capture rate in lab tests, but it is much harder to capture carbon from mobile sources than from stationary sources. Gas stations would have to develop CO_2 handling and storage capacity, presumably.

A third option would be to continue to utilize liquid fossil fuels and offset the resulting emissions through the use of direct air capture systems that remove carbon dioxide from the atmosphere and then permanently sequester it in underground geologic formations.

A fourth option would be to reduce CO_2 production in the extraction and processing of liquid fossil fuels (e.g., reducing flaring).

Ammonia, which is made by combining hydrogen and nitrogen, contains no carbon and can be stored in liquid form at moderate temperature or pressure conditions and then utilized in ICEs. It could be a cost-effective tool for meeting 2050 decarbonization targets, especially in marine shipping applications. Major hurdles include fuel production costs (as compared to incumbent fuels), infrastructure and engine costs, NOx emissions, and handling safety. Research suggests progress can be made on all fronts. A near-term advantage of ammonia over hydrogen is that it can more easily be stored on board in the quantities required to be effectively utilized in a slightly modified ICE, allowing for quicker conversion of marine fleets. Ammonia is already produced in massive volumes (roughly 170 million metric tonnes [MMT] per year) for non-transportation uses, and production could scale up by an order of magnitude (the key factor is the cost of the necessary hydrogen). Total conversion of the shipping sector to ammonia would require approximately 500MMT NH3/year. This incremental ammonia would have to be net-zero-carbon on a lifecycle basis.

On *aviation fuel*, there is a strong consensus that the industry will continue to require liquids over the long term; non-liquid options like batteries and gaseous fuels do not look viable in the foreseeable future. Biomass-derived sustainable aviation fuels (SAFs) made from waste feedstocks are central to the aviation industry's current decarbonization strategy. The supply of sustainable and economically viable biomass is likely too limited to allow the use of biofuels in multiple transportation subsectors as well as for biomass-fueled power and heat production, so if aviation consumes much or all of the available biomass, the rest of the economy will have to pursue other decarbonization strategies to get to net-zero CO_2 emissions. It is unclear whether sustainable biofuel production (which currently constitutes a small fraction of total biofuel production) could scale up enough to satisfy demand from the aviation industry. If the supply of sustainable biofuels is too low to meet the aviation sector's demand, the industry can turn to synthetic hydrocarbons (discussed below) or continued use of hydrocarbons offset by direct air capture of CO_2.

Biofuels could technically power most types of vehicles, but scalability looms as a significant obstacle. Biofuels, particularly those made from waste feedstocks, could play an important role in transportation decarbonization, especially for aviation (see above), but that role will be constrained by the high uncertainty around the volume of biofuels that can be sustainably harvested (taking into

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[14] DT Anialis, C Thorne, D. Cebon, "Decarbonising the UK's Long-Haul Road Freight at Minimum Economic Cost," Centre for Sustainable Road Freight—Technical Report CEUD/C-SFR/TR17, July 2020.

account lifecycle climate impacts, among other factors). Consequently, the question is what is the best use for sustainable biofuel within the broader transportation sector, and aviation is frequently cited as the answer. Other transportation end-uses (LDVs, HD trucks, marine vessels, rail) are better positioned to accommodate other energy carriers (e.g., electricity and hydrogen-based fuels) and typically have fewer and/or less stringent fuel-related technical and safety constraints than aviation, so the willingness-to-pay for supply-constrained biofuels may be lower in other transportation subsectors than in the aviation industry.

An interesting conundrum exists with respect to biofuels' oft-cited role as a "bridge fuel" to zero-carbon energy carriers: for biofuels to meaningfully contribute to transportation decarbonization, the market needs better biofuels (e.g., drop-in fuels made from waste and other feedstocks that have a low lifecycle carbon intensity rating), but the investments required to deliver such fuels will be hard to justify if the expectation is that the transportation market will move away from biofuels in 10 or 20 years.

Synthetic hydrocarbons, also known as power-to-liquid (PTL) fuels, are made by building drop-in fuels from hydrogen and carbon atoms that have been derived through climate-friendly processes. These processes might include electrolysis powered by zero-carbon electricity (to make hydrogen) and direct air capture (DAC) powered by a zero-carbon power plant (to get carbon). (The zero-carbon electricity would be made with renewable, nuclear or other zero-carbon energy sources). As with hydrogen-based fuels, the potential supply of synthetic hydrocarbons fuels is technically unbounded except for siting constraints that may impede the construction of necessary production equipment. However, their production costs are currently very high, and future costs depend on the future costs of DAC.

6.4 Gaseous fuels

Initiative participants discussed several gaseous fuels and fuel feedstocks, particularly hydrogen, but also conventional and renewable natural gas.

Hydrogen could be used to drive down emissions from a range of transportation applications, but heavy duty and long-distance freight trucks offer the most compelling near-term opportunity for hydrogen utilization in the transportation sector. (See Section 7 on Integrated engine, fuel and vehicle potential greenhouse gas (GHG) reduction and cost). However, the freight sector would need to compete for hydrogen with the manufacturing industry, which influences hydrogen price and availability.

The carbon intensity of hydrogen depends on how it is produced. It is imperative to pursue both "blue"/CCS and "green"/electrolysis production pathways—that is, pathways that make hydrogen from fossil fuel feedstocks but drastically reduce or eliminate the associated GHG emissions through carbon capture and storage systems, and pathways that extract hydrogen from water through electrolysis powered by renewable or nuclear energy. The cost of different production methods is partly tied to location and accessible resources; overall, blue hydrogen is generally cheaper than green hydrogen and will likely continue to be for some time, but locational differences in the cost of natural gas, the cost of renewable power, access to carbon storage resources, and other factors will ultimately be determinative. Intersectoral "coupling" between the power sector (which may produce, store, and use hydrogen to manage grid imbalances) and transportation end-users could reduce the cost and increase the availability of hydrogen in both sectors, but more research is needed to understand these relationships.

As discussed in Section 11 on Infrastructure, hydrogen infrastructure buildout is a daunting challenge. Although both EVs and FCEVs require substantial refueling or recharging infrastructure, existing electricity infrastructure provides a much larger initial platform for expansion relative to hydrogen, at least in developed countries. While hydrogen production and pipelines exist, the total scale is miniscule relative to electricity, and current hydrogen demand is primarily in industrial areas, as opposed to the vast electricity infrastructure that already exists in commercial and residential areas. Thus the "chicken and egg" problem for hydrogen as a transportation sector energy carrier is larger than it is for electricity. Another option is to have distributed hydrogen production. This would require a decarbonized electric grid or distributed carbon capture, and the build-out of a fueling network (similar to EV charging infrastructure).

While aircraft will likely require liquid fuel for the foreseeable future (see above), an eventual shift to hydrogen-fueled aviation is possible. The technology and cost barriers are familiar, but significant: all the aircraft in the fleet would need to be replaced, the operating costs of those aircraft could increase by up to 30%, the low density of hydrogen would limit flight range, and airports would have to be retrofitted for hydrogen liquefaction and delivery systems.

Renewable natural gas (RNG) offers interesting potential, but also large uncertainties, and questions remain about the definition of RNG and how renewable and sustainable it is in the long-term. The Electric Power Research Institute and the California Air Resource Board define RNG as methane derived from non-fossil sources, which includes gas that forms passively at landfills and dairy operations and is then captured, as well as gas that is actively made by gasifying biomass material. In the latter case the carbon intensity of RNG depends on a lifecycle assessment of the GHG emissions associated with the production, harvest, and conversion of the biomass feedstocks. The extreme negative emissions attributed to manure-based RNG in California arise not from any carbon removal but from the fact that dairies and concentrated animal feeding operations are not currently required to mitigate methane pollution. By capturing and using methane to make energy and emitting CO_2 in the process, RNG-to-energy systems essentially replace the high global warming potential associated with methane emissions with the lower global warming potential associated with CO_2 emissions.

In the longer term, GHG emissions from the agricultural sector are likely to be regulated, at which point the negative carbon intensities (CIs) for manure-based RNG will likely change to low but positive CIs. Total supply of RNG is likely to be too small to meet existing demands for natural gas, so the availability of RNG to the transportation sector will be limited.

Finally, nuclear-powered propulsion, especially the use of small modular reactors on marine vessels and other vehicles, is an option that receives comparatively little attention or investment, but should be kept open. Nuclear power could also be a zero-carbon source of electricity for hydrogen and ammonia production through electrolysis.

SECTION 7

Integrated Engine, Fuel and Vehicle Potential GHG Reduction and Cost

The integration of advanced engines and fuels shows the alternative paths to GHG reduction as well as their effects on total cost of ownership (TCO) and limitations in terms of maximum potential to reduce emissions. The appropriate comparisons are based on the projection that average future crude prices will stay relatively low due to supply and demand expectations (although price volatility is possible), and that existing technologies will fight extinction by reducing costs to stay ahead of new competition. Climate policies could change the price picture, especially for fossil fuels.

7.1 Light-Duty Vehicles

While much of the current attention is focused on electric vehicles, improved ICE efficiency in combination with biofuels or zero-carbon fuels offer additional pathways for GHG reduction, with further GHG reduction possible from advances in onboard carbon capture and storage (CCS) technology.

ZEVs can achieve very high levels of GHG reductions if they are widely used and if the fuels they use have net-zero GHG emissions on a lifecyle basis. Thus electrification of light vehicles can reach very high levels of GHG reduction (>95%) across the subsector provided that electric vehicles successfully reach near 100% penetration and the electric grid is decarbonized. Some vehicles, like emergency vehicles and taxis, may also have to be capable of using liquid fuels so that a major power outage does not cripple local transport. Attaining these levels is technically feasible, but requires either (1) significant changes in consumer preference, or (2) ambitious policies. In addition, large reductions up to 80% in the carbon content of electricity are clearly doable, but the last 20% is difficult. At 80% grid carbon reduction and 80% EV penetration, the net GHG reduction is about 84%.

Fuel cell vehicles fueled by hydrogen appear to face an uphill struggle as current costs for both the vehicle and fuel are high. Impressive strides have been made in fuel cell technology and cell cost reduction, but costs of on-board hydrogen storage ($1000/kg of hydrogen) and the distribution and refueling system for compressed hydrogen are high. It is not clear whether there is a path

Table 1: Light-Duty Vehicles

Pathway	Per-vehicle GHG reduction*	TCO Effect	Consumer Impact other than TCO	Notes
Efficiency (hybrid)	55%	Possible reduction	Minimal	Least disruptive
Efficiency + cellulosic E25	65%	Modest	Minimal	Cellulosic EtOH may be feasible <$3 gallon, octane benefit
Efficiency +E25 + on board CCS	80%	Unclear	Unclear	CCS could capture 50% of tailpipe CO_2
Efficiency + Drop in E-fuel	90+%	High increase	Minimal	Fuel cost could increase by 3x
BEV with 80% Grid Decarbonization	90+%	Modest	Significant for some	Challenges for long-distance driving and some rural users; benefits for some users in more urban settings
Fuel cell vehicle with e-hydrogen and 80% grid decarbonization	90+%	Significant increase unless and until fuel cell and H2 costs drop with large- scale production and long term projections	Minor once refueling infrastructure well established	Requires major investments in fuel infrastructure and introduction of new vehicle technologies

*Relative to a 2020 baseline. Baseline CO_2 intensity assumed is 420 g/kWh and baseline for light vehicles is 355 g/mi.

for light-duty FCVs to be competitive on a TCO basis with conventional or electric vehicles, but they may be a winner for large cars or trucks due to range and refueling time.

7.2 Heavy-Duty Trucks

Heavy-duty trucks span a wide variety of sizes, weights and uses that make general sector-wide analyses impossible. Two large sub-sectors in this class of vehicles are light-heavy trucks (10,000 to 16,000 lb. gross weight) serving urban pick-up and delivery markets and long-haul heavy-trucks (over 50,000 lb. gross weight) transporting cargo that account for a large fraction of total GHG emissions. The costs and benefits of alternative engine-fuel strategies for the light-heavy urban delivery market are shown below. While additional efficiency benefits from technology are limited, electrification appears to be cost-effective even now and will likely be a dominant solution for this sub-sector.

In contrast, electrification of the long-haul heavy trucks segment is quite difficult with batteries, but the use of catenary powered electric trucks, with relatively small batteries to allow short-range off-catenary operation, is a possibility. This would require massive infrastructure development along major trucking corridors so that electric power is available on overhead wires, with attractiveness dependent on how the infrastructure is funded, and it is not clear whether such a system offers advantages over current or expanded rail networks. Battery- or catenary-based electrification solutions may apply to other truck subsectors depending on weight, payload and duty-cycle, but some subsectors such as logging, mining and construction trucks may have no choice except low-carbon liquid fuels to attain high levels of GHG reduction.

Fuel cell powered trucks using hydrogen are also a possibility although the high cost of hydrogen at the retail outlet is a difficult challenge to overcome. Recent analyses indicate that long-haul trucks powered by hydrogen fuel cells offer substantial advantages in terms of total cost of ownership and other performance metrics when compared to similar trucks powered by batteries (key factors include the substantial space and weight consumed by sufficiently sized battery packs [which negatively impacts payload], the range of HD BEVs, and

Table 2: Urban Delivery Vehicles

Pathway	Per-vehicle GHG reduction*	TCO Effect	Consumer Impact other than TCO	Notes
Efficiency	25%	Possible reduction	Minimal	Least disruptive
Efficiency	40%	Modest increase	Minimal	B20 Supply limited, not a solution for the entire market
Efficiency + on board CCS	62%	Unclear	Unclear	Onboard carbon storage could lower cargo capacity
EV with 80% grid decarbonization	90%	Cost-effective	Modest	Possible that EV may be optimal market choice
Fuel cell vehicle with e-hydrogen and 80% grid decarbonization	90%	Significant increase unless and until fuel cell and H_2 costs drop with large- scale production and long- term projections	Minor once refueling infrastructure well established	Requires major investments in fuel infrastructure and introduction of new vehicle technologies

*Relative to a 2020 baseline. Baseline CO_2 intensity assumed is 420 g/kWh and baseline for light vehicles is 355 g/mi.

the time needed for battery recharging). Shorter-haul, centrally-fueled, hydrogen-powered trucks offer benefits that go beyond GHG reductions, such as reduced conventional emissions and reduced noise—both of which are specifically important in disadvantaged communities located in urban areas, near ports, etc. This same use case is also probably well served by battery electric vehicles and drayage, and regional trailers do not have the same range requirements as long-haul trucks.

Table 3: Long-Haul Heavy Freight Vehicles

Pathway	Per-vehicle GHG reduction*	TCO Effect	Consumer Impact other than TCO	Notes
Efficiency	35%	Possible reduction	Minimal	Least disruptive
Catenary with 80% grid decarbonization	~93%	Possible reduction	Fixed lines could affect routing flexibility	Requires major infrastructure investment (who pays?)
Efficiency + on board CCS	62%	Unclear	Unclear	Onboard carbon storage could lower cargo capacity
EV with 80% grid decarbonization	90%	Very high first cost	Refueling time	Payload loss, first cost are formidable barriers
FCEV with low-carbon hydrogen	>80%	Increase over incumbent systems, but likely lower than BEVs	Scarcity of refueling stations could affect routing flexibility	Requires major infrastructure investment in refueling

*Relative to a 2020 baseline. Baseline CO_2 intensity assumed is 420 g/kWh and baseline for light vehicles is 355 g/mi.

7.3 Commercial Aircraft

Aircraft efficiency improvements of 26% between 2020 and 2050 are expected in a business-as-usual scenario, although there is uncertainty. There is the potential to introduce very advanced aircraft designs that could provide up to 50% reduction by 2050, but this is not without economic and safety challenges. Airlines have suggested biofuels as the main solution for reducing GHG emissions by nearly 100% by 2050, but it appears that global sustainable biofuel supply must be largely reserved for aircraft for this to be a fleetwide solution (there is significant uncertainty around the supply of sustainable biofuels). Fuel costs will increase by 2x over jet fuel. Biofuel/jet fuel blends may provide lower-cost reduction, similar to biodiesel for trucks, but such blends are less effective at reducing GHG emissions. Drop-in e-fuels appear to be a very high-cost solution at this point with a significant impact on ticket prices.

Battery electric propulsion appears possible post-2030 for short-haul (<300 mile) regional aircraft, but this segment accounts for very little of total aircraft GHG emissions. Electric hybrid propulsion for medium-haul routes (300 to 1000 miles) could reduce GHG emissions for those routes by another 25-30%, but with significant speed reduction for some design solutions. It is not clear at this point whether hybrid electric aircraft will have significantly lower emissions than advanced non-hybrid designs. This depends on what routes they are used on (as well as the design specifics). If they are restricted to very short-haul routes it is quite likely hybrid electric aircraft will reduce route-level emissions compared to advanced non-electrified designs, but in this case they would not be able to meet much of the demand.

Green hydrogen is receiving some attention from the EU as a possible solution, but storing liquid hydrogen (LH2) potentially requires tanks that are much larger than the tanks used for jet fuel. The LH2 cost may also be too high, and it may only work for short-haul aircraft with an operating radius of less than about 1000 miles. This technology is in an early stage of development, but the high cost of LH2 could make this approach as expensive as drop-in e-fuels. See Appendix 3 for an overview of vehicle and engine options and issues for aircraft.

7.4 Marine

The International Maritime Organization (IMO) aims to cut emissions from international shipping by at least 50% by 2050 compared to 2008, requiring a large part of the international shipping fleet to transition to net-zero-carbon fuels. Ammonia could potentially power this low-carbon fuel transition.[15] The NH_3 would have to be net-zero or nearly net-zero-carbon (i.e. Natural Gas+CCS, or carbon-neutral electricity [hydro, solar, wind, nuclear, etc]. Alternatives such as LNG can only play a transitional role. The estimated current costs of “blue” or “green” ammonia is approximately 3-7 times more expensive than conventional marine fuel.

U.S. shipping is now responsible for 80 million tonnes of CO_2 emissions and this figure could increase. For the U.S. shipping fleet to decarbonize in line with the IMO Initial Strategy, by 2050 demand for marine ammonia in the U.S. could reach 47 million tonnes. Marine ammonia could be made from renewables or potentially nuclear power or fossil power with carbon capture and storage. The transition pathway would involve a combination of policy, R&D, private investment, and coordination among multiple stakeholders. “Pilot routes” could help facilitate early stages of the transition. Routes for first movers and pilot vessels such as a Rotterdam-to-Houston route for ammonia carriers, or a Southern California-to-China route for an ammonia-powered container ship could offer the testbed for trying out ammonia as a fuel in a controlled environment. These routes could help to ascertain the technical, financial, economic and safety developments necessary to make marine ammonia a reality.

So far, it is unclear which measures could achieve the emissions reduction targeted by the IMO (much less, reductions that are consistent with the Paris Agreement), but it is unlikely that it will be through technology alone. Slow steaming has become standard practice in maritime shipping since the start of the global economic crisis over a decade ago. It has reduced emission levels of shipping by an average of 11%. The latest ships are designed for low speeds, however, and continued excess capacity and a possibly increased fuel tax burden will help to keep speeds low. Ships could change over to LNG use for 15% carbon reduction, if methane leakage is reduced well below current levels, or even to ammonia for a much more significant reduction, although the shift to ammonia will need an intense globally coordinated effort.

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[15] https://www.poseidonprinciples.org/wp-content/uploads/2019/06/Lloyds-Register_Decarbonisation-Transition-Pathways_2019.pdf.pdf

SECTION 8

Freight

Freight movement accounts for about half of global transportation fuel consumption (although it is less than half in the U.S.), with commercial trucks comprising 60-70% of freight energy consumption. Rail, marine and cargo aircraft account for much of the remainder, with the energy fractions for each varying significantly by country and by domestic vs. international freight. Freight movement is highly correlated with GDP, so the highest growth is expected in developing countries where GDP growth is expected to be much higher than in OECD countries.

The type of goods moved by each transport mode varies significantly, with rail and marine carrying most bulk commodities like crude, mineral ores, and coal, while aircraft and trucking are typically used for higher-value consumer goods. The decarbonization potential varies not only by the type of goods, but also by haul length, and the discussion of decarbonization potential must be specific to these variables.

As shown in Figure 3 on the next page, the Dutch agency Connekt laid out a scenario for reducing freight emissions by 83% (also described as increasing CO_2 productivity by a factor of 6). The figure shows how measures could add up for consumer goods logistics. More than half of the target is achieved by efficiency improvements and the remainder with changes in vehicle design and operation (including engines).

The same figure for bulk goods (Figure 4) shows the reverse picture: efficiency improvements can only absorb a small portion of the overall target. The majority of reduction of carbon emissions has to come from vehicle design and operations. The difference is mainly due to the specific distances, modes used, networks operated and products of the two segments.

Figure 3: Cascade graph for long distance transport of non-perishable consumer goods (Connekt et al. 2017)—Y-axis indicates the % cumulative improvement in productivity per unit CO2 (600 = 600%, or 6x, increase)

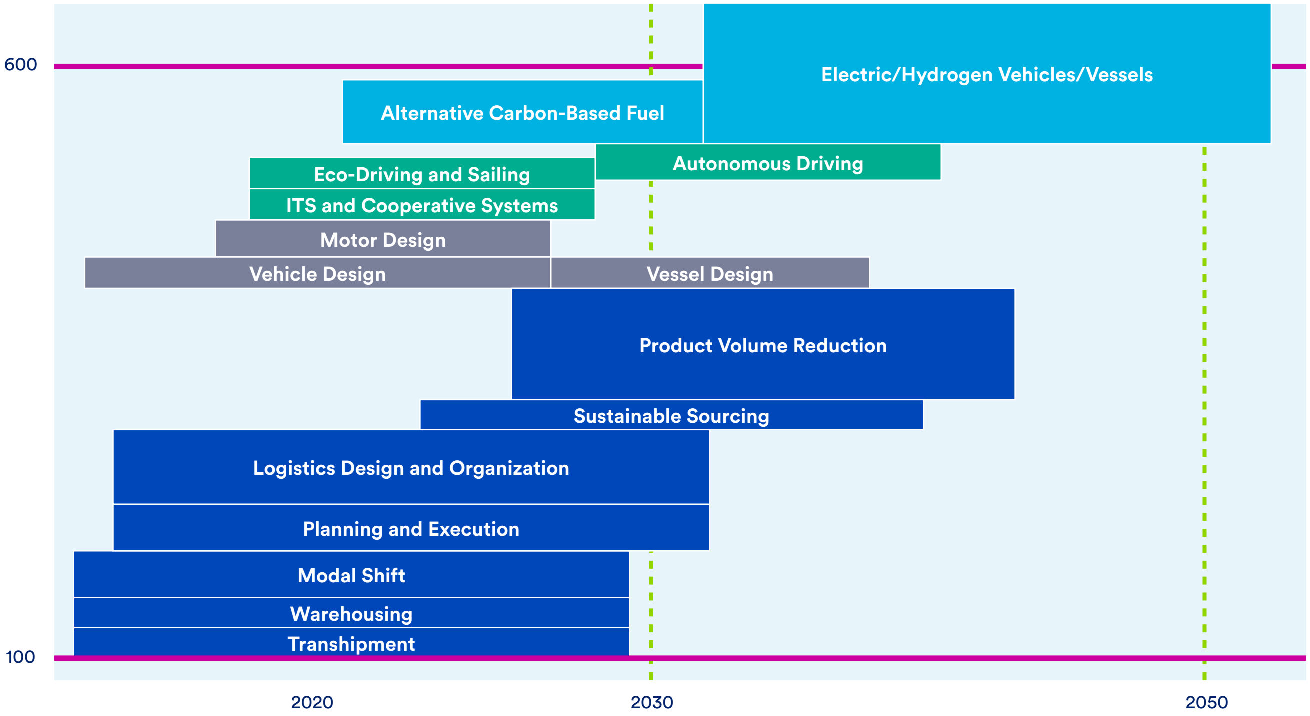
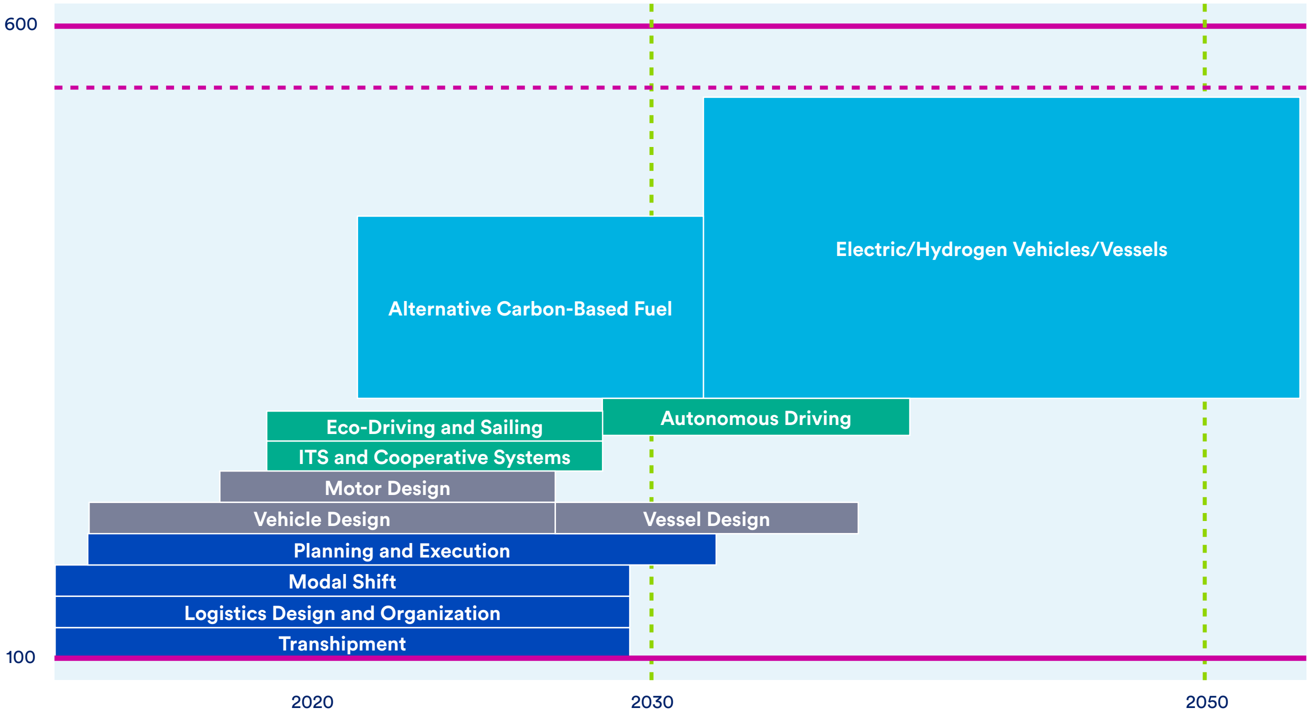


Figure 4: Cascade graph for long distance transport of dry bulk goods (Connekt et al. 2018)



As shown below, the overall framework for decarbonization of freight transport developed by the EU in its Innovation Roadmap recognizes five categories of freight and logistics measures that together determine GHG emissions reductions, namely:

- Improving energy efficiency with new technology, optimizing truck driving and fleet maintenance
- Reducing the carbon content of fuel, or through electrification
- Optimizing transport modes by moving from air to other modes and from trucking to rail or waterways
- Increasing asset utilization by consolidating and optimizing vehicle loads, and having “open” transport systems to reduce empty backhaul
- Reducing freight transport demand by measures such as restructuring the supply chain and “reshoring” of manufacturing

Figure 5

Categories based on A. McKinnon 2018

Reduce Freight Transport Demand	Optimize Freight Transport Modes	Increase Asset Utilization	Improve Fleet Energy Efficiency	Reduce Carbon Content of Energy
• Supply chain restructuring • Localization and nearshoring • Standardized modules/boxes • 3D printing • Dematerialization • Decentralization • Consumer behavior	• Modal shift urban • Modal shift air to other modes • Modal shift trucking to rail/ waterways • Multi-modal optimization • Synchromodality	• Load optimization • Load consolidation and asset sharing • Modular packaging and boxes • Open warehouses and transport networks • Increase storage density and energy efficiency	• Cleaner and efficient technologies • Efficient vehicles and vessels • High capacity vehicles/duo trailers • Driving behavior • Fleet operation • Fleet maintenance	• Cleaner diesel • Electric/hybrids • Biofuels • Hydrogen • CNG/bio-LNG • Fuel management

Multiple measures have been developed within each category, and the EU roadmap contains expert judgment about the impact and feasibility (translated into the expected time to successful deployment) of these categories of measures. The EU analysis found that some of the measures that are being implemented already today show a significant efficiency impact along with proportional carbon emissions reduction. EU experts suggested the need to consolidate and estimate the effects of ongoing and near-term actions and to focus on the necessary preconditions to achieve a major next step until 2030 with actions not considered feasible today. There are many near- and medium-term low-hanging-fruit opportunities, especially in vehicle efficiency and logistics (10-15% in fuel efficiency and 10-15% in logistics) and for the medium-term, an additional 10% potential for logistics.

8.1 Efficiency improvements and electrification

While all of these measures can contribute to freight emission reduction, the largest contributions are expected from improvements to energy efficiency and from electrification. As noted in other sections, efficiency improvements in trucking and air transport possible over the next 30 years range from 30% to 40%. There is less room for policy-driven improvement in efficiency for freight than for personal transportation, as freight businesses have been more motivated to improve efficiency because they are competitive businesses for which fuel costs are a significant portion of operating costs. Low-carbon fuels such as biodiesel or sustainable jet fuels can result in additional reductions. Biofuels are supply limited and can likely displace only a small share of conventional fuel used globally for freight. Synthetic hydrocarbons are technically unlimited but currently very expensive. Electrification has significant potential in short-haul urban delivery of consumer goods, and the use of battery electric trucks with ~100-mile range appears to be cost-effective even at current prices. In medium- and long-haul applications, it is not clear whether battery electric trucks will be successful, but options such as catenary-electric trucks may be possible beyond 2030 with adequate investment in electric infrastructure. Electric aircraft, however, are likely for only short-range regional operation and could emerge by 2035; hydrogen aircraft are a longer-term potential solution. Fuel cell-powered trucks also hold some promise, especially on a total cost of ownership basis for long-hauls, and because of co-benefits for short-hauls.

8.2 Modal shift and asset utilization

The last two decades have witnessed significant changes in asset utilization in OECD countries. In the U.S., container shipping from marine-to-truck and truck-to-rail are now well established, and container shipping over long distances now typically includes road-to-rail transfer for many types of goods. This has become so prevalent that large interstate truck sales have stagnated over the past decade despite substantial GDP growth following the 2008-09 recession. Future gains in mode sharing are likely to be modest since much of the possible shift has been accomplished.

For intercontinental freight transport, air freight and maritime are the main and often only alternatives for transport. Per tonne of freight moved, ships emit less carbon than aircraft, so a modal shift could have positive impacts. The type of goods moved are vastly different however, and the niche where the two modes compete is very narrow. Rail on these longer distances, for the type of freight moved by both modes, has a negligible role as it lags both in performance (compared to air) and cost (compared to maritime). Within continents, much of the freight that is nominally carried by a door-to-door air cargo services is trucked between airports and to and from shippers. Mode shift to high-speed rail has been studied but has shown to be unlikely because it is costly to arrange the movement between the high-speed rail hub station and the final origin or destination.

Opportunities to further re-organize shipping and trucking logistics appear to lie in capacity utilization. A number of internet-based firms have emerged in many countries to match trucking services to shippers' requirements in real time, and studies show further efficiency gains are possible. However, substantial additional gains appear unlikely as the production and consumption of goods are not uniformly distributed geographically so that empty or less-than-truckload operation cannot be reduced below a certain level.

For marine transport, consolidation through collaboration between carriers has introduced alliances to align the deployment of ships; the number of independent carrier groups or alliances has been reduced from 17 to 4 in the past 25 years so that the future potential here is limited. However, within these alliances, it is estimated that improved vessel and fleet management (via advanced control software and digital platforms) could yield an additional CO_2 reduction of more than 20%. Efficiency gains of similar magnitude could be achieved for air cargo networks, especially when spurred by stronger policy regimes.

SECTION 9

Aviation

In 2018, the International Council on Clean Transportation estimated that aviation was responsible for around 2.4% of global CO_2 emissions from fossil fuel use. This fraction is likely to rise as other sectors decarbonize, because aviation's climate impacts are particularly difficult to reduce. Long fleet lifetimes and technology development timescales, physical limits on fuel specific energy, and high projected long-term growth rates in global demand combine to create a challenging environment for deep decarbonization. Until recently, industry projections envisaged a continuation of historical 4-5% per year growth rates in global passenger-km aviation demand, but this could conceivably be lower in the post-COVID era.

Although CO_2 emitted per passenger-km has been reducing at rates faster than current industry targets of 1.5%/year (about 20% reduction every 15 years), the gap between demand growth and mitigation potential likely means that long-term direct passenger aviation CO_2 emissions will continue to increase in the absence of aggressive new policies. Much air freight is transported on passenger planes, and freighter flights, which account for around 10% of total aviation CO_2, are subject to similar issues. About 50% of air freight (by mass) was transported in passenger aircraft pre-COVID, but during the pandemic the share of freighters was larger. Anticipated near-future technological improvements, such as ultra-high bypass ratio engines, changes in wing-aspect ratio and increased use of composite materials, will be needed to maintain current rates of improvement in fuel economy while advanced new architectures could increase the rate to about 30% reduction every 15 years. Both electric and hydrogen-fueled aircraft are feasible post-2035 options, but face significant challenges related to technology development and infrastructure provision and appear at this time to be very expensive solutions. However, efficiency gains cannot by themselves produce sufficient emissions reductions if rapid global demand growth continues.

This picture is further complicated by aviation's non-CO_2 climate impacts. The combined climate impact of NOx emitted at altitude, contrails and contrail-induced cirrus cloud formation can exceed aviation's CO_2 climate impacts and would be reduced by only small amounts by the use of drop-in alternative fuels. However, the magnitude of these impacts is less certain and is more dependent on the metrics and time horizons used to compare them, making political consensus harder to achieve on mitigation strategies. Contrail avoidance has the potential to strongly reduce aviation non-CO_2 impacts, potentially at the cost of an increase in fuel use and hence CO_2. Similarly, trade-offs exist between aviation CO_2, noise and local air quality impacts. Recent studies, however, indicate that contrails can be avoided by flying outside of ice supersaturated regions in the atmosphere and that increased CO_2 from such actions could negate less than 1% of the climate benefits. Unfortunately, there are no incentives to do this presently.

There are operational improvements that could reduce GHG emissions, including:

- More direct routing through improved air traffic control
- Matching the range and load of aircraft to optimum efficiency, but this may involve stops on long-haul routes
- Formation flying where aircraft behind the lead aircraft take advantage of the wake energy
- Shifting demand to high-speed rail. This would be possible only along some high-demand corridors of less than 500 miles length

More direct routing is being implemented already (e.g. the U.S. Next Generation Air Transportation System (NextGen) and Single European Sky Air Traffic Management Research initiatives) but the others would be logistically difficult. In total, these improvements could reduce GHG emission by ~5%.

Projections of emission reductions within the aviation sector itself often rely on drop-in biofuels (implying large-scale availability of biomass for aviation fuel production) or power-to-liquid (PTL) fuel using low-carbon electricity (which currently has projected costs significantly above conventional aviation fuel). Drop-in biofuels can be used in the current jet fleet without any engine modification and are already in limited use in some airports such as Los Angeles and Brisbane, typically due to specific agreements between biofuel producers and airlines and as blends with Jet A fuel. Costs in 2019 for some different biofuels were 2x to 5x of those for conventional jet fuel. This is a very significant price increase, but not unprecedented. Fuel cost is 25-30% of total airline operating cost and even a doubling of fuel costs would have large effects on ticket prices and demand. As discussed earlier, aviation should most likely be a priority for limited biomass supply but other sectors may compete for it. LNG is also a possibility that might modestly reduce CO_2, but would require the use of pressurized cryogenic storage tanks on aircraft. LNG has the advantage of low cost and wide availability compared to all other fuel options, but it is unclear whether it is worth a significant investment to switch to a fuel with only modest GHG benefits compared to current aviation fuels.

Thus multi-sectoral pathways to net-zero often assume positive aviation CO_2 emissions, which are then offset by negative emissions in other economic sectors. Both the EU Emission Trading Scheme and the International Civil Aviation Organization's Carbon Offsetting and Reduction Scheme for International Aviation, the two current largest-scale attempts to address aviation CO_2, do so largely via the purchase of emission offsets or allowances from other sectors.

The key takeaways are that there are many possible pathways. These include: maximizing the use of efficiency technology to 2050; avoiding regions where contrails are formed, improving operational procedures, using blends of biofuels and, once available, synthetic fuels, researching the use of hydrogen and LNG for feasibility by 2035, and reducing demand. Most of the pathways are difficult to implement without significant disruption to the industry. It appears that by combining multiple pathways, significant but not total decarbonization may be possible. The International Air Transport Association (IATA) has a goal of 50% reduction by 2050 that assumes heavy reliance on low-carbon biofuels. A faster and more complete shift to low-carbon biofuels or synthetic fuels is technically feasible, but likely very costly.

SECTION 10

Infrastructure

There are more than a billion cars, trucks, trains, ships, planes and other powered vehicles on the planet. Nearly every person and business in the world consumes transportation services in some form. Providing those vehicles with the net-zero-carbon energy they need to operate, wherever they operate, will require an extensive set of parallel supply chains.

Like many other countries, the United States has been a one-technology (ICE) and one-infrastructure (liquid hydrocarbons, primarily petroleum) transportation market for more than a century, and it is now apparent how difficult it is to change when externalities call for a new approach. The future of transportation is unlikely to rely on a single solution. Multiple infrastructures cost more, but they also provide resilience and can be a hedge against unexpected failure of a single pathway.

Decarbonization strategies that are fully or partially compatible with existing fuels systems and engines (e.g., efficiency improvements, biofuels, drop-in synthetic fuels) present different, usually smaller, infrastructure challenges, but their cost and scalability constraints may limit the extent to which they can contribute to deep decarbonization. Strategies that depend on electricity and hydrogen-based fuels offer a clearer pathway to full decarbonization, but present larger and/or more complicated infrastructure challenges.

While emission reduction strategies that are compatible with existing fuel systems and engines—such as carbon neutral biofuels and synthetic fuels—require a smaller set of changes to downstream infrastructure when compared to a transition to electricity- or hydrogen-powered transportation, they do present significant upstream challenges. Countries like the United States, Brazil, Indonesia, and Germany already have substantial biofuel production and distribution infrastructure that can be built upon, but the vast majority of that production is supplied by first generation feedstocks that offer only modest environmental benefits at best (e.g., corn starch, soybean oil, palm oil). Shifting to feedstocks, like waste biomass and energy crops grown on degraded land, can result in biofuels with substantially lower lifecycle carbon intensity, but such a shift will likely necessitate the development of a new, more flexible, and less permanent type of supply chain.

Similarly, pulling together carbon-neutral streams of hydrogen and carbon to make climate-beneficial drop-in synthetic fuels will require new upstream infrastructure, such as direct air capture units to extract carbon dioxide from the atmosphere and electrolyzers and/or gas reformers with carbon capture and storage to make hydrogen.

Electrification presents different challenges and opportunities. Transportation decarbonization scenarios that depend on high BEV penetration rates (which is to say, most of the scenarios) necessarily depend on a corresponding ramp-up in net-zero-carbon electricity production. U.S. economy-wide decarbonization models typically project that U.S. electricity load will increase by 2-4x by 2050, and transportation decarbonization is seen as a major driver behind that load growth. According to modeling from Evolved Energy Research (2020), 24% of generic electricity load in the United States in 2050 will be associated with demand from battery electric vehicles. (Moreover, 68% of the power used to make hydrogen through electrolysis would be associated with demand from fuel cell vehicles.) Massive new investments in the infrastructure used to produce and transmit net-zero-carbon electricity to the transportation market will be necessary around the world.

Electricity is already ubiquitous in the developed world, but interconnection and vehicle charging infrastructure still requires substantial additional investment, and analysts debate whether scaling up EV charging capacity will benefit from economies of scale. Some analysts expect the per-unit cost of building out charging infrastructure to increase, rather than decrease, because new demand from fast charging stations will require new investments to shore up the electrical grid; other analysts disagree. In the current U.S. context, most EVs are charged at home.

The story in the developing world is different, of course. Reliable electrical grids are less ubiquitous, infrastructure investment budgets are more constrained, and the vehicles purchased for personal and commercial transportation are often previously owned and older in vintage. Each of these factors suggests that a rapid transition to electric- and hydrogen-based transportation in the developing world faces qualitatively distinct, and perhaps larger, challenges than in OECD countries. On the other hand, markets with fewer vehicles and smaller fueling infrastructure may struggle less with the path dependency issues that complicate transportation technology transitions in richer countries.

Hydrogen-based transportation may require substantially more infrastructure investment, but has potential benefits compared to electrification, especially in some medium- and heavy-duty use-cases, in terms of efficiency, refueling time, range, and ultimate cost. Hydrogen poses a bigger chicken and egg infrastructure investment problem than electricity, but the societal return on that investment may make the effort worthwhile nonetheless.

Substantial penetration of vehicles that run on hydrogen-based fuels (e.g., hydrogen fuel cell-powered trucks and ammonia ICE-powered marine vessels) will require a massive scale-up of nearly every part of the supply chain: hydrogen production, ammonia synthesis, pipelines, tankers, delivery trucks, fueling stations, etc. At the production end, a significant increase in the demand for hydrogen (or ammonia) with low- or zero-lifecycle GHG emissions will necessitate a huge expansion of net-zero-carbon electricity generators (renewable or nuclear or CCS) along with a complementary fleet of electrolyzers, or legions of new CCS-equipped gas reformers, or (most likely) a combination of both production technologies.

Some of the infrastructure challenges can be managed through industrial planning and policy support. For example, public and private investment could turn key shipping ports around the world into hubs that link together zero-carbon hydrogen and ammonia producers (CCS- and/or electrolysis-based), CO_2 management systems (compressor stations, pipelines, etc.), storage facilities (massive portside ammonia tanks), and ammonia export assets (tanker ships) with a variety of hydrogen and ammonia end-users (hydrogen fuel cell-powered forklifts and long-haul freight trucks, ammonia-fueled tankers and containerships, etc.). Similar opportunities could be centered around airports, railyards, and trucking depots, while also addressing environmental justice concerns in the surrounding communities.

The use of electricity and hydrogen as energy carriers in the transportation sector may create intersectoral coupling benefits. The timing and volume of the production of both energy carriers (electricity and hydrogen) could help increase the utilization of key components of a zero-carbon energy production infrastructure. Intelligently timed BEV charging might serve as a sponge for electricity produced during off-peak hours, thus improving the cost equation for a massive build-out of variable renewable electricity generators (e.g., wind and solar plants). Similarly, it may be possible to manage transportation-related demand for hydrogen and ammonia fuels (and the associated investments in production capacity) in ways that complement (rather than compete with) the fuels' use as mid- or long-term storage mediums for power and as substitute fuels for heavy industry. More research is needed to understand the benefits and the limitation on intersectoral coupling.

Transportation infrastructure challenges are likely to be not just substantial, but also multifaceted. It increasingly makes sense to view the transportation sector as an integrated energy system rather than a consumer of energy products. Building the necessary infrastructure will require an investment of work, time, and money into multiple platforms. Stakeholders need to ensure that the various pieces of the solution set do not “fall off the table” due to a narrow focus on just one decarbonization technology (e.g., electric LDVs).

Government has an important role to play in infrastructure development, as policy measures can (and must) accomplish a lot on production and distribution of energy for transportation services. Along with the LCFS/ZCFS framework, examples of useful policy measures to promote key infrastructure innovations and improvements include research and development support, tax credits for deployment, permitting support, and, less directly, ZEV mandates, and government procurement policies.

APPENDIX 1

Participant List

Katelyn Bocklund
Great Plains Institute

Domagoj Baresic
Energy Institute, University College London

Rebecca Ciez
Purdue University

David Cleary
Aramco Americas

Vincent Costanzo
Aramco Americas

Steve Csonka
Commercial Aviation Alternative Fuels Initiative

Dominic Dicicco
Ford Motor Company

Lynnette Dray
Energy Institute, University College London

Gopal Duleep
H-D Systems

Alessandro Faldi
Exxon Mobil

Lew Fulton
University of California at Davis

Josh Goldman
Via

David Greene
University of Tennessee at Knoxville

Judi Greenwald
Greenwald Consulting LLC

Chad Hunter
National Renewable Energy Laboratory

Brendan Jordan
Great Plains Institute

Kara Kockelman
University of Texas

Ken Laberteaux
Toyota

Jonathan Lewis
Clean Air Task Force

Jeremy Martin
Union of Concerned Scientists

Brad Olsen
Recurrent Advisors

Steven Przesmitzki
Argonne National Laboratory

Deborah Salon
Arizona State University

Tom Stricker
Toyota

Lori Tavasszy
Delft University of Technology

Tom Walker
Clean Air Task Force

Brian Weeks
Gas Technology Institute

APPENDIX 2

Net-Zero-Carbon Fuels and Energy Carriers for Ground Transportation

	Electricity	Biofuels	Zero-Carbon Energy Carriers (H_2, NH_3)	Synthetic hydrocarbons (DAC + H_2*)	Oil or gas with direct air capture (DAC) or other offsetting actions
Key current trends	Global average electric vehicle (EV) sales 2% in 2019 and growing.	Up to 10% blends of ethanol and biodiesel/ renewable diesel in 2020 in some locations, but virtually no advanced biofuels production.	Hydrogen and ammonia are important industrial chemicals, but not significantly used as a transportation fuel.	Currently no known synthetic hydrocarbon commercial sales for transportation fuel anywhere in the world.	DAC (with carbon sequestration) under development. Some industries capturing process CO_2 and sequestering it or using it for various processes.
Key technology options	Battery electric and plug-in hybrid electric vehicles (BEV and PHEV).	Advanced fuels from waste biomass or feedstocks that do not compete with existing land uses (not plant oils or grains).	H_2, NH_3 or other zero-carbon fuel from electrolysis or biomass gasification.	Electrolysis or biomass gasification to synthesis gas, followed by polymerization to hydrocarbon chain fuels.	Oil/gas mature and cheap; DAC is technically viable but expensive.
Key infrastructure options	Electric grid, charging infrastructure systems.	Biofuel-petroleum blends are compatible with current ICE vehicles and infrastructure.	Hydrogen used in fuel cell electric vehicles (FCEV), needs storage and refueling infrastructure.	Compatible with current ICE vehicles and infrastructure; need CO_2 transport and storage infrastructure.	Compatible with current ICE vehicles and infrastructure; need CO_2 transport and storage infrastructure.
Critical path issues	Battery cost reduction; charger installation to support rapid sales.	Advanced technology cost reduction and scaleup; supply of sustainable biomass.	H_2 production (via electrolysis and/ or gas reforming with CCS) and infrastructure scaleup to help reduce costs.	Electrolysis, Fischer-Tropsch and other technology scale-up to help reduce costs.	DAC (with carbon sequestration) development and scaleup, identification of suitable locations.
Path dependencies	EVs will require heavy investments in electric distribution and charging infrastructure.	Ethanol currently limited to 10-15% of gasoline pool for today's vehicles; "modern" renewable diesel can be blended to 100% with diesel fuel.	H2 primarily for use in FCEVs; NH_3 has unclear vehicle application, but potential for marine.	Can be fully compatible with today's ICE vehicles.	None for vehicles and fuels, but will need DAC and carbon storage development and infrastructure buildout.

(table continued)

	Electricity	Biofuels	Zero-Carbon Energy Carriers (H_2, NH_3)	Synthetic hydrocarbons (DAC + H_2*)	Oil or gas with direct air capture (DAC) or other offsetting actions
Timing issues	Advancing rapidly, potential for 10-30% shares in many countries by 2030; feasibility of scale-up by 2050 depends on critical path issues described above.	Large-scale production unlikely by 2030; feasibility of scale-up by 2050 depends on critical path issues described above.	Early deployment phase; potential for 5-20% sales shares in most markets by 2030; feasibility of scale-up by 2050 depends on critical path issues described above.	Large-scale production unlikely by 2030; feasibility of scale-up by 2050 depends on critical path issues described above.	Large-scale DAC (with carbon sequestration) implementation unlikely by 2030 though a few large-scale facilities are possible; feasibility of scale-up by 2050 depends on critical path issues described above.
Benefits	Low energy and running cost, zero emissions.	Compatible with ICE vehicles, possible low lifecycle GHG emissions.	Operation in FCEVs, rapid fueling and longer range than BEVs.	Compatible with ICE vehicles, potential very low lifecycle GHG emissions.	Oil/gas inexpensive, compatible with ICE vehicles.
Costs	High vehicle costs, but dropping.	Conventional biofuels are within 20% of the cost of petroleum fuels; advanced biofuels up to 2x cost.	$3-5/gallon of gasoline equivalent (GGE) for H_2 from SMR, $15 for H_2 from electrolysis; may drop significantly by 2030 if scale is increased; FCEV purchase costs up to 30% higher than gasoline vehicles.	Very high costs of production ($10-30/GGE) likely until high volumes, mature market achieved.	Will require very large volumes of possibly very expensive DAC to offset fossil fuel use.

*made from CH_4 reforming + CCS or electrolysis from zero-carbon electricity

APPENDIX 3

Net-Zero-Carbon Fuels and Energy Carriers for Aviation

	Electrification	**Biofuels**	**Zero-Carbon Fuels (H_2* & NH_3)**	**Synthetic hydrocarbons (DAC + H_2*)**	**Oil plus Direct Air Capture**
Key current trends	Numerous projects developing small electric aircraft; some cancelled (e.g. Airbus E-Fan X). Range limitations mean hybrid electric may be a more attractive option pre-2050. Small, air taxi-type electric aircraft (mainly to substitute for short-distance ground trips) different from electric aircraft to substitute for conventional passenger/freight aviation.	Drop-in aviation biofuel increasing, but mainly demonstration projects – e.g. LAX/United/ Altair collaboration. Biofuel is a key component of industry projections with CO_2 emission reductions. Question is whether aviation should be a priority for limited biomass supply when its use may achieve greater total CO_2 reduction in other subsectors (e.g. CCC, 2019).	Limited development at present. Both have been investigated (e.g. CRYOPLANE project for H_2; RAL/ Oxford University for NH_3) but have potential problems with infrastructure/ fleet turnover and non-CO_2 negative externalities. Some evidence that industry interest in electric aircraft may pivot to H_2 (e.g. Airbus announced Sept 2020 it is working on hydrogen aircraft designs).	PTL fuels are a key part of some projections in which the sector achieves net-zero (e.g. EC, IEA). However, cost issues at present have led to limited development. Planned demonstrator plant in Norway (Norsk e-Fuel). SNG with adapted aircraft design is also a possibility.	Most commonly-considered use of DAC is via PTL fuel, but fossil kerosene plus offsets linked to DAC are another possibility.
Key technology options	Most electric aircraft in development are air taxi-type vehicles (battery energy density improvements could change this). Hybrid electric aircraft designs include the Boeing/ NASA SUGAR project (these theoretical rather than in-development designs may inform manufacturer decisions).	Five approved pathways; only HEFA-SPK** is technically mature so likely to dominate short-term. Cellulosic biomass feedstock may offer the best potential CO_2 reduction/cost/ land use tradeoff.	Limited development at present, but Airbus has announced initial hydrogen aircraft concepts. Hydrogen is probably more likely than NH_3, but technology challenges remain. Hydrogen aircraft can be fuel cells (may be more suited to short-range) or direct combustion.	Main option investigated in the literature is drop-in FT-SPK using renewable electricity.	No additional technology required in-sector, but need DAC plus CO_2 storage.
Key infrastructure options	Battery electric aircraft would require charging or battery swap infrastructure at airports. Range limitations (severe for battery electric which would be limited to short-haul flights initially, less severe for hybrid electric) could...	Aviation biofuel production now is usually at plants that mainly supply road vehicle biofuel, a much larger market. Significantly more production infrastructure would be required to make a non-negligible impact on aviation CO_2 emissions.	Extensive changes to refueling infrastructure would be required, as well as fuel production infrastructure.	Fuel production infrastructure would be needed (similarly to biofuel). Few demonstration projects at present. As with biofuel, there is the potential to fuels for multiple sectors from one facility.	No within-sector infrastructure requirements. Requires suitable DAC and CO_2 transport and storage capacity.

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	require network reconfiguration. Some designs might require runway extension at minor airports; conversely, some e-Taxi aircraft designs are vertical takeoff and landing (VTOL).	Fuel supply infrastructure may be required to deliver the biofuel to the airport. Biofuel can be mixed with the general fuel supply at airports and usually blended with fossil Jet A (as now only up to a 50% blend is certified for use).			
Critical path issues	Long lifetime of aircraft in fleet (~30 years), long development times (~ 10 years) and long production runs of existing aircraft models (can be up to 20 years) mean radical changes in technology that cannot be applied to existing aircraft take a long time to percolate through the fleet. Questions as to whether airlines would buy aircraft with limited range.	Road vehicle biofuel market is much larger, limiting incentives for producers to invest in aviation biofuel. Biofuels are not cost-competitive with fossil Jet A at present (roughly 2x price of fossil Jet A in 2019; Pavlenko et al. 2019) so policy decisions with regard to biomass use in aviation and other sectors will have a strong influence on uptake. Current 50% blend limit with fossil Jet A (higher blends theoretically possible with blending in aromatics).	As with electric aircraft, new aircraft models' long development and fleet turnover timescales means likely limits impact pre-2050. Technology development issues around volume and/or pressurization of fuel. Hydrogen aircraft contrail impacts are uncertain: they are most likely lower than for conventional aircraft, but could be worse.	Main issue is that the projected costs (~ 5x fossil Jet A price in 2019) have led to limited interest in getting aviation PTL fuels to/beyond demonstration stage. SNG with adapted aircraft would require some changes to aircraft design and so could only take place on a longer timescale.	Similar to other sectors using DAC.
Path dependencies	Dependent on development of batteries with suitable energy density (> 800 Wh/kg). Limited number of manufacturers means individual manufacturer decisions about technology prioritizationare key. Also dependent on oil price. Charging infrastructure construction needed in parallel with technology development.	Suitable production and distribution infrastructure needs to exist for widespread uptake of aviation biofuel. Costs and availability critically depend on demand from other sectors for biomass and on policy.	Requires manufacturer decisions to invest in developing the technology and airport decisions to invest in the infrastructure necessary to support it. Must meet safety and local air quality standards (globally and at any key airports with stricter standards).	For drop-in PTL, suitable production and distribution infrastructure needs to exist for widespread uptake, even if costs can be brought down; however, in many cases existing distribution infrastructure can be used. Similarly, dependent on DAC technology development/deployment and supply of low-carbon electricity.	Similar to other sectors using DAC.

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	Must meet noise standards (globally and at any key airports with stricter standards; the increased weight means electric aircraft may not be quieter).			SNG fuel would require industry decisions to invest in LNG aircraft development (though this may also be motivated by lower fuel cost).	
Timing issues	Viable battery electric aircraft (and to some extent hybrid electric aircraft, depending on design) require battery energy densities that are not possible with Li-ion (> 800 WH/kg); requires further development of advanced battery chemistries. Along with development and fleet turnover timescales this likely limits impact in the fleet pre-2050.	Can be used in existing aircraft (up to 50% blend at present). The main constraints on adoption are production capacity and cost. competitiveness with fossil Jet A.	Dependent on technology development and fleet turnover timescales. If not included in next generation aircraft designs (2030-35) then impact pre-2050 is likely to be small.	Drop-in PTL can be used in existing aircraft (up to 50% blend at present), so the main timing issues are bringing the technology to/beyond demonstration stage, production capacity and achieving cost competitiveness with fossil jet A. SNG would require development of LNG-compatible aircraft and so would additionally be subject to development and fleet turnover timescales.	Similar to other sectors using DAC.
Benefits	All-electric aircraft would eliminate direct CO_2, NOx and contrails from aircraft. Hybrid electric aircraft would have less impact depending on the degree of hybridization.	Fuel lifecycle CO2: wide range depending on feedstock/process/land use change (e.g. 80+% reduction for cellulosic biomass FT-SPK); also potential reduction in contrails due to lower particulates. Limited changes in current networks and airport infrastructure required.	Hydrogen has a high enough energy density that range would be less of a problem (though size of tanks limits the benefits for long-haul aircraft). Local air quality improvements. Likely decrease in contrails (though uncertainty range is large).	Depends on the source of electricity. 80+% reduction in fuel lifecycle CO_2 has been projected (e.g. Pavlenko et al. 2019).	Environmental benefits similar to other sectors using DAC. No changes in current networks and airport infrastructure required.

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Costs	Electric aircraft could be cost-competitive with conventional aircraft designs, depending on fuel prices and the costs and replacement frequency of batteries (e.g. Schafer et al. 2019). Noise could be as high as conventional designs; a different frequency mix could make it more or less acceptable to communities near airports.	Currently not cost-competitive with Jet A without additional carbon price (HEFA fuels were around 2x fossil Jet A price in 2019; Pavlenko et al. 2019), but may become cost-competitive (e.g. Schafer et al. 2014), particularly if carbon policy is applied.	McKinsey et al. (2020) EU Clean Skies report claims around a 10-30% operating cost increase per passenger for short/mid-haul (including fuel, direct infrastructure and capital costs) – up to 50% for long-haul, with additional long-term costs if airport layouts require reconfiguration.	Current estimates are PTL aviation fuel would be 5x or more the price of fossil Jet A as of 2019 (Pavlenko et al. 2019), largely due to renewable electricity costs.	Similar to DAC costs in other contexts.
Key drivers and uncertainties wrt **1. Innovation** **2. Markets/ investment** **3. Behavior/ behavioral change** **4. Public policy**	Although many small, electric aircraft are in development, range limitation means it's uncertain whether aircraft capable of extensive substitution for current flights could be brought to market. Potentially lower cruise speed, short/stopping flights and different noise signatures may affect passenger demand (though there will be environmental benefits). Main current relevant policy is Norway's commitment to electric short-haul flights by 2040.	There is already small-scale use of commercial aviation biofuel at a small number of airports (e.g. Bergen, Brisbane, Los Angeles, Oslo, Stockholm). Scaling up would require further investment in production infrastructure Biofuels are incentivized by some current policies (e.g. exempt from EU ETS; discounted based on fuel lifecycle CO_2 in CORSIA; optional inclusion in EC RED II). A key question is which sectors should/will get priority use of biomass in the case of limited supply.	Development of hydrogen aircraft would require a coordinated decision between manufacturers, airports and others to develop the technology and infrastructure. Because projected costs are higher than conventional designs, this would likely require significant policy support. Potential safety/certification issues need to be overcome.	Limited investment in drop-in PTL demonstration projects at present due to high projected costs. Similar policy environment to biofuels.	Similar issues to more general offsets for aviation (e.g., CORSIA, EU ETS). One potential issue is competition against cheaper, lower-quality offsets.

*made from CH_4 reforming + CCS or electrolysis from zero-carbon electricity

**HEFA/SPK = Hydroprocessed Esters and Fatty Acids

APPENDIX 4

Overview of Vehicle and Engine Options and Issues for Aircraft

	ICEs	Fuel Cells	Batteries	Other?
Key current trends	Increases in bypass ratio; gearing; open rotor; boundary layer ingestion (see ATA & Ellondee, 2018).	Could be part of hydrogen aircraft design (potentially as hybrid with direct combustion).	Need development of batteries with >800 Wh/kg to be viable for 737-size aircraft (e.g. Li-S or Li-Air).	Different airframes and operational changes (e.g., improving routing) may also have an impact.
Key technology options	Ultra-high bypass ratio (UHBR) is likely in the next generation of aircraft (2030-35). Open rotor is at demonstration stage (e.g. Safran) but no suitable airframe as yet.	Clean Skies 2020 report (McKinsey et al. 2020) estimates fuel cell systems targeting system power densities of 1.5-2kW/kg including cooling systems is required.	Key requirement is energy density (Li-ion is insufficient for designs replacing even typical short-haul passenger flights; Li-S or Li-air and >800 Wh/kg likely needed; Gnadt et al. 2018). May need separate high specific power batteries for takeoff in all-electric aircraft.	Higher wing aspect ratio (likely in the next generation of aircraft); increased use of composite materials (also likely); blended wing body (BWB) aircraft; air traffic control (ATC)/ routing improvements; operational adjustments to better match operations to design range.
Key infrastructure options	Open rotor may need tarmac reconfiguration and changes to schedules to accommodate slower cruise speed. UHBR engines would be compatible with existing infrastructure.	Same infrastructure issues as hydrogen aircraft.	As for electric aircraft. Different refueling options refueling – battery swap (higher cost, but potentially faster turnaround time) or charge (lower cost, but lower aircraft utilization possible).	Higher wing-aspect ratio may require tarmac reconfiguration (or folding wing tips). BWB aircraft would require significant infrastructure adaptation at airports. ATC changes require suitable equipment on board aircraft, at airports and at air navigation service providers (ANSPs). Better matching missions to design range would require substantial network change.

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	ICEs	Fuel Cells	Batteries	Other?
Critical path issues	UHBR and open rotor both increase engine diameter, requiring suitable airframe changes. Potential safety/tarmac reconfiguration required for open rotor. Issue of airline/passenger acceptance for open rotor (may have lower cruise speed and/or higher noise).	Same issues as hydrogen aircraft.	Main critical path issue is whether/when suitable battery energy densities can be achieved. A secondary issue is whether a workable business model exists for airlines running range-limited electric aircraft to enable the technology to become established.	Composites, wing-aspect ratio and improved and improved ATC are likely developments with some use in existing aircraft/ systems. BWB aircraft would need additional R&D (e.g., pressure vessel issues; travel sickness; evacuation). Network change issue makes better matching to design range less likely.
Path dependencies	Development of a compatible airframe. Oil price dependency (fuel can be 30% of airline operating costs and fuel cost reduction is one of the main drivers of aircraft fuel efficiency improvements). For UHBR, NOx-reduction technology requirement to meet NOx standards (as there is a trade-off between NOx and CO_2).	Same dependencies as hydrogen aircraft.	Main dependency is on development of battery technology (however, the energy density issue is less acute in other sectors).	Network reconfiguration (in the case of better matching range to design range). Pressure vessel technology for BWB aircraft.
Timing issues	Next generation of aircraft (after A320neo/737MAX generation) anticipated 2030-2035. This model of aircraft will likely be dominant in the fleet in 2050.	Same issues as hydrogen aircraft.	Unlikely to have a significant impact on global aviation emissions pre-2050 (e.g. Schafer et al. 2019; ATA & Ellondee, 2018). For all-electric aircraft, initial substitution is ultra-short-haul flights (<10% of global aviation emissions).	Increased use of composites, high wing-aspect ratio, improved ATC all likely to affect current/next generation of aircraft (the others are less likely to be adopted at all).
Benefits	UHBR has roughly 20-30% lower fuel use than comparable year-2000 technology. Open rotor benefit is around 30% and also emits less NOx. Boundary layer ingestion (BLI) by itself would provide around 3-4% reduction in fuel use.	Same benefits as hydrogen aircraft. Note that fuel cells are more likely in short-haul aircraft.	Same benefits as battery-electric aircraft, i.e., climate impact reduced to that of electricity generation and almost no local emissions. The use of electric propulsors would likely decrease maintenance costs.	Composites – around 10% fuel burn reduction compared to year-2000 tech; high aspect ratio wing – 11-15%; BWB – potentially 30% for twin-aisle aircraft; improved ATC typically a few percent; better matching of design range potentially up to 45% for some flights but overall system benefit much lower (Poll, 2011).

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	ICEs	Fuel Cells	Batteries	Other?
Costs	UHBR likely cost-competitive (ATA & Ellondee, 2018). Open rotor may be cost-competitive (e.g. Dray et al., 2018), but would need slower cruise speeds to achieve full benefit.	Same costs as hydrogen aircraft – i.e., likely increase over existing operating costs.	As with battery-electric aircraft, potential to be cost-competitive when the technology becomes available (Schafer et al. 2019) but uncertain.	Projected lower total operating costs for future aircraft using higher wing-aspect ratio and more composites (ATA and Ellondee, 2018); similarly ATC improvements. BWB aircraft would likely have a higher list price than conventional-technology alternatives, but might be cost-competitive once fuel cost decreases are factored in (Dray et al. 2018).
Key drivers and uncertainties wrt **1. Innovation** **2. Markets/ investment** **3. Behavior/ behavioral change** **4. Public policy**	UHBR is likely in the next generation of aircraft. Open rotor further development would require manufacturer investment in a compatible airframe (unlikely given limited extra benefit over UHBR). BLI is at low technical readiness level (TRL) and is relatively unlikely on future aircraft designs as the benefits are relatively small.	Same issues/drivers as hydrogen aircraft, i.e., some interest due to high mitigation potential without range limitation, but would require substantial R&D and new infrastructure, and adoption would be subject to long development and fleet turnover delays (therefore limited benefit likely pre-2050). Development is already supported by policy (research into low-carbon aircraft was a condition of the French government's Airbus bailout).	Because high battery energy density is a more stringent requirement in aviation than other sectors, not all improvements in battery technology developed for other sectors will benefit aviation (but some will). Similar other issues as for electric aircraft, above.	For technologies not anticipated on the next generation of aircraft, development through to commercial aircraft models would likely need additional support. Network reconfiguration would be unlikely to occur without policy incentives (and agreement might be hard to obtain on suitable policy).