Results in Engineering 4 (2019) 100060

Contents lists available at ScienceDirect

Results in Engineering

journal homepage: www.editorialmanager.com/rineng/Default.aspx

Diversity in transportation: Why a mix of propulsion technologies is the way forward for the future fleet

P.K. Senecal [a,*], Felix Leach [b]

[a] Convergent Science, United States
[b] University of Oxford, United Kingdom

ABSTRACT

Transportation today is almost exclusively powered by the internal combustion engine (ICE). Although engines have become significantly cleaner and more efficient over the last few decades, human health and environmental concerns have led several governments around the world to propose bans on diesel and gasoline cars. The electrification of transportation, while often touted as the only way to mitigate vehicle emissions, comes with its own set of concerns and challenges that must be considered when developing future transportation technologies. Furthermore, there is still significant untapped potential in both ICE concepts and the fuels they use.

This paper argues that hybrid systems are the fastest way to reduce CO_2 emissions from vehicles and that, when judged on a life-cycle basis, the vehicle technology with the least environmental and health impact is highly region dependent. Therefore, a mixture of transportation technologies is necessary in the future fleet. It is hoped that the recommendations provided in this paper will prompt policymakers to set targets for emission reduction instead of implementing bans on specific technologies, so industry can focus on developing the best solutions for each situation.

Introduction

The internal combustion engine (ICE) is often recognized as one of the greatest inventions of all time. Since the first gasoline-powered vehicle was developed by Karl Benz in 1885, the ICE automobile has changed the world, providing unprecedented levels of freedom and access. However, the combustion engine was not the only transportation technology that sought to replace the horse and cart. In the late 1800s, the combustion engine competed with the electric motor and the steam engine for dominance in the transportation industry. The ICE succeeded for many of the same reasons it remains popular now: its high power density, long range, low cost, and convenience.

Today there are more than one billion cars on the road, and over 99% of them are powered by an ICE [1]. The world has benefited significantly from this machine. Having a car increases one's economic opportunities—King et al. show that US households without cars are about twice as likely to be poor as households with cars [2]. Access to automobiles has been, and continues to be, a means to lift people out of poverty.

But there is a downside to having so many cars on the road. Globally, 10–15% of greenhouse gas (GHG) emissions come from transportation, including land, air, and marine transport (see, *e.g.* Ref. [3]). In addition, emissions such as particulate matter (PM) and oxides of nitrogen (NO_x) can be detrimental to human health. As a result, government mandates on fuel economy and emissions levels have been implemented around the globe. A review of the current regulations related to tailpipe emissions and CO_2/fuel economy can be found in Ref. [4]. For light duty vehicles, it is expected that automakers will need to annually improve fuel economy by 3–6% in major markets [4].

The automotive industry has continually innovated to meet government regulations over the last several decades. Cars are significantly cleaner and more efficient today than they were in 1975. Unfortunately, these achievements have been partly overshadowed by scandal in recent years. In 2015, the United States Environmental Protection Agency found that Volkswagen intentionally programmed some diesel engines to activate emissions controls only during lab testing and not during real-world driving—outside of the lab, the engines emitted NO_x up to 40 times the limit in the US [5]. This scandal, dubbed “dieselgate”, led to fines, jail time, and a large stain on the ICE.

Prior to dieselgate, the electrification of transport started making a comeback in 1997 with the introduction of the Toyota Prius. The Prius was the first mass-produced full hybrid vehicle, using both a battery and an ICE. As of January 2017, global sales of the Prius family had surpassed six million units [6], and it is considered the most successful hybrid of all time.

A fully electric vehicle also entered the market in the mid to late 1990s. The EV1 from General Motors was the first “mass produced” battery electric vehicle of the modern era by a major auto manufacturer,

* Corresponding author.
E-mail address: senecal@convergecfd.com (P.K. Senecal).

https://doi.org/10.1016/j.rineng.2019.100060
Received 28 October 2019; Accepted 2 November 2019

with around 1,100 cars produced between 1996 and 1999. However, GM determined the EV1 was not commercially viable and stopped the program after investing more than one billion dollars in production, infrastructure, and marketing. The cars were destroyed, but some of the technology lives on in GM's hybrid and fuel cell vehicles [7].

The destruction of the EV1 fleet motivated the founding of a new company, Tesla Motors (now Tesla, Inc.), in 2003 [8]. Tesla released its first fully electric vehicle, the Roadster, in 2008 and went on to release the Model S, the Model X, and the Model 3. In 2018, after ten years in the market, Tesla became the best selling electric vehicle (battery electric vehicle and plug-in hybrid electric vehicle) car maker in the world, with over 245,000 units sold worldwide [9]. To put this number into context, around 80 million total cars were sold in 2018, and 0.3% of those were Tesla vehicles. In addition, Tesla has posted a negative net income for eight of the last ten quarters [10]. But despite its low volume sales and lack of profits, Tesla has transformed the automotive industry by demonstrating that a car can be both electric and exciting at the same time.

Government bans

The promise of electric vehicles and the political pressure of reducing our fossil fuel use has led governments to start announcing bans on ICE vehicles. To give an idea of how widespread the ban statements have become, we have attempted to summarize our current understanding in Table 1. It is important to note that Table 1 represents a snapshot in time, as government statements can frequently change.

In reviewing Table 1, a few questions arise: (1) what exactly do these bans mean? (2) will the bans actually happen? and (3) do the bans make sense? We first attempt to address question (1) in the last column in the table and with additional discussion here.

As shown in the table, China has announced that they will phase out the manufacturing and sale of fossil fuel cars; however, no timeframe has been given [11]. Additionally, according to an analysis by the Center on Global Energy Policy, switching to electric vehicles will have little impact on CO_2 emissions in the short term, since coal is the dominant method for producing electricity in China. In fact, some studies have shown that CO_2 emissions in China are currently greater for electric vehicles than conventional vehicles on a life-cycle basis [12]. This is in large part due to the significant CO_2 generated from the production phase of battery electric vehicles [13].

Costa Rica made headlines in 2018 after President Carlos Alvarado said during a speech that by 2021, the country will have removed gasoline and diesel from transportation [14]. Many news outlets interpreted these remarks to mean that Costa Rica would ban fossil fuel-driven transportation; however, Costa Rica is not planning to officially implement a ban. Instead, their intent is to phase out diesel and gasoline from transportation through policies and incentives aimed to render fossil fuels obsolete [15].

In France, the proposal that would officially turn the climate plan laid out in 2017 into law is currently being debated in parliament and, at the time of writing, has not yet been approved [16]. Denmark proposed in 2018 to end the sale of petrol and diesel cars by 2030, but had to withdraw their proposal as it would have violated EU rules [17].

India unveiled an ambitious plan to end the sale of petrol and diesel cars by 2030. However, reality seems to have hit recently, as Prime Minister Narendra Modi made a statement assuring that conventional engine vehicles and EVs can co-exist in India [18]. The United Kingdom has called for an end of *conventional* cars by 2040, but it is important to note that even mild hybrids are not included in this ban as they are not considered conventional cars. Indeed, the question of what exactly these bans mean is a complicated one.

Question (2), “will the bans actually happen?”, is not something we can answer in this work. However, given India's recent pullback, it seems possible that other countries will follow suit.

Question (3), “do the bans make sense?”, is, of course, the focus of this paper. How do we reconcile the bans with projections that the total number of cars will double by 2040? What will power all of those cars? Of course, many believe that electric vehicles (and possibly fuel cell vehicles) will swiftly take over the market. However, electric vehicles are not without their share of problems, including major environmental and health risks, as described later in this paper. By examining the pros and cons of both combustion engines and electric vehicles, an argument is made to support a portfolio of technologies, including ICE vehicles, electric vehicles, and hybrids, in the future fleet. It is hoped that policymakers will consider these arguments before instituting bans in their jurisdictions.

Electric vs electrified

Before discussing the advantages and disadvantages of various transportation technologies, it is important to understand the terminology. There has been a great deal of confusion both in the media and in government announcements between *electric* vehicles and *electrified* vehicles. An electric powertrain is commonly understood to mean only battery electric vehicles (BEVs), which run solely on an electric motor. An electrified powertrain encompasses mild hybrids (MHEVs), full hybrids (FHEVs), and plug-in hybrids (PHEVs), all of which include an ICE.

The confusion between electric and electrified vehicles has manifested itself both in announcements of government bans, as addressed in the previous section, and in announcements from car manufacturers. For example, in July 2017, Volvo announced that their cars would be all electric starting in 2019 [31]. Many understood this to mean that Volvo would make only BEVs from that point on, with the BBC reporting that Volvo was “the first traditional carmaker to signal the end of the internal combustion engine” [32]. However, the announcement from Volvo clarifies that from 2019, all of Volvo's vehicles will be fitted with an electric motor—which can include PHEVs, FHEVs, and MHEVs in addition to BEVs. As of October 2019, conventional ICEVs are still available to purchase from Volvo.

Unintended consequences can arise from the confusion surrounding electric and electrified vehicles. Electrified vehicles are clearly a part of the future of transportation, but if policymakers are not aware of the role the ICE plays in powering these vehicles, they may create legislation and allocate funds for research and development in a way that excludes ICEs. This could lead to missed opportunities for improving the ICE and, thus, miss out on further reduction of vehicle emissions.

Current market and future projections

When comparing different transportation systems, it is helpful to examine the current market. How many electric vehicles were sold in 2018? According to Ref. [33], 2.1 million plug-in vehicles were sold, up 64% from 2017. In total, this represents 2.2% of the total light duty vehicle sales in 2018. 69% of the plug-in sales were fully electric (BEVs), while the remaining 31% were PHEVs. Thus, about 1.5% of all new cars sold in 2018 were battery electric. Of the 2.1 million plug-in sales in 2018, 56%, or about 1.2 million units, were sold in China [33]. This highlights the significance of China in developing the EV sector.

It is clear from these numbers that ICEs are in the vast majority of vehicles on the road today, including newly sold vehicles. But what is projected? Most projections show that at least half of the cars on the road in 2050 will still be powered by ICEs [34].

The EV30@30 Campaign was launched at the 8th Clean Energy Ministerial in 2017 with the aspirational goal of 30% of new vehicle sales in 2030 to be EVs (BEVs and PHEVs) within the member countries. Even with this campaign to speed up the deployment of electric vehicles, hitting this goal would still mean that 70% of new vehicles sold in 2030 would be conventional ICE and full or mild hybrid vehicles (and of course the PHEVs will contain an ICE as well). Vehicle quality is going up, so cars are generally lasting longer. The average age of a car on the road is about 12 years old [35]. Even under the EV30@30 scenario and looking out to 2040, most cars will have ICEs in them. As a result, continuing to improve the ICE is essential.

Table 1
Proposed government bans on ICEs in transportation. The first column lists the countries that have announced or proposed bans on ICEs; the second column gives the year in which the proposed ban would take effect; the third column details what the ban would encompass; and the last column addresses whether the proposed ban would really mean the end of the ICE in transportation in that country.

Country	Ban Commences	Scope	Will ICEs actually be banned in transportation?
China	TBA	Phase out manufacturing and sale of fossil fuel cars [11]	No additional information available
Costa Rica	2021	Remove gasoline and diesel from transportation [14]	The goal is to transform the light-duty vehicle fleet to be zero emissions, running on renewable energy not derived from fossil fuels. For freight transportation, the goal is to adopt modalities, technologies, and energy sources that emit zero or the lowest possible emissions. ICEs will not be explicitly banned [19].
Denmark	2030	Phase out sales of new petrol and diesel cars in 2030 and new plug-in hybrid cars in 2035 [20]	In 2018, Denmark proposed to end the sale of ICEVs by 2030, but the plan has since been withdrawn as it would have violated EU rules [17].
France	2040	End sales of vehicles that emit greenhouse gases [21]	According to Transport Minister Elizabeth Borne, France aims to ban the sale of vehicles that consume fossil fuels by 2040. France will help car makers "switch to electricity, hydrogen and possibly biogas", leaving open the possibility of ICEs that run on alternative fuels [16].
India	2030	End sales of petrol and diesel cars [22]	Prime Minister Narendra Modi has recently announced that ICEVs and EVs can co-exist in India in the future [18].
Ireland	2030	Ban the sale of new fossil fuel cars [23]	The ban is for new non-zero emissions small vehicles and does not include heavy freight vehicles. As there is a lack of EV substitutes for the heavy freight sector, the government will support the uptake of compressed natural gas vehicles, which contain ICEs [23].
Israel	2030	Ban the import of diesel and gasoline cars [24]	The goal is for all new cars to be electric, but for buses and trucks to run on either electricity or compressed natural gas [25].
Netherlands	2030	All new cars should be zero-emissions vehicles [26]	The Netherlands recognizes that for some methods of transportation, such as heavy goods road traffic, inland shipping, maritime shipping, and aviation, there is currently no suitable alternative to the ICE. For these modes of transit, the government is investigating the use of advanced biofuels, renewable Power-to-X fuels, and synthetic fuels [26].
Norway	2025	All new light vehicles, new city buses, and new light commercial vans should be zero-emissions vehicles [27]	The transition to zero-emissions heavy vehicles will take place over a longer period of time, meaning the ICE is likely to remain for years beyond 2025 [27].
United Kingdom	2040	End conventional car and van sales [28]	The ban includes only conventional gasoline and diesel cars and does not include hybrid vehicles. For heavy goods vehicles, which are also not included in the ban, the government is investing in the development of innovative fuel technology, such as advanced low-carbon fuels derived from wastes and residues [29].
Sweden	2030	End sales of new petrol- and diesel-driven cars [30]	No additional information available

Internal combustion engine vehicles

ICEVs have been the dominant transportation technology for a century, but it is worth acknowledging that, like all technologies, they are far from perfect. ICEs, by burning fossil fuels, emit CO_2 and other pollutant emissions (mainly NO_x, particulate matter, hydrocarbons, and carbon monoxide). These emissions have negative effects on human health and the environment, and their elimination is a key focus for proponents of electric vehicles. Since the widespread adoption of fuel efficiency standards, CO_2 emissions from vehicles have fallen substantially. In Europe, for example, emissions decreased by 31% between 2000 and 2016 [36]. Similarly, many vehicles now emit near-zero levels of pollutant emissions (*i.e.*, below the accuracy level of the instrumentation used to measure them) in real driving scenarios, which will be discussed in the Real Driving Emissions section below.

Apart from emissions, another downside of ICEs is that their energy efficiency is low in absolute terms—typically up to 40–50% [37,38]. However, there are thermodynamic limits to efficiency, and efficiency typically scales with size [39]. Leading Combined Cycle Gas Turbines (CCGTs) today operate at 64% efficiency on a power station scale [40]; in that context, ICE efficiencies are not so terrible—and indeed those CCGTs will be generating much of the electricity required for an EV. Another disadvantage of ICEVs is that energy is wasted through friction braking, which converts fuel energy to (useless) heat. This issue has been mitigated in hybrid vehicles, which recover almost all of the braking energy with very little wasted through the friction brakes. Engine efficiency is discussed further in the Efficiency Potential section below.

ICEVs are relatively noisy, which is either an advantage or disadvantage depending on user perception. But as automakers have worked to create quieter cars, a new problem has emerged—electric vehicles are now *too* quiet. Pedestrians, especially those with visual impairments, rely on vehicle noise to determine if a car is approaching. As a result, electric cars are around 40% more likely to hit a pedestrian than conventional ICEVs [41]. As of July 2019, the EU implemented a law requiring that all new electric vehicle models must emit a noise when traveling at low speeds, at which EVs are practically silent.

ICEVs require somewhat complicated transmission systems to allow for the low-speed torque and high-speed power requirements from the vehicle, while keeping the ICE in relatively efficient operating areas (as well as avoiding low-speed stall). Additionally, ICEs and their associated systems require regular maintenance. Engine oil changes are recommended about every 10–15,000 miles, and urea solution (also known as DEF or AdBlue), which is required in SCR aftertreatment systems, should be topped off at 5–7000 mile intervals. Other regular maintenance items include air filters and timing belts. Vehicles without ICEs obviously do not have these maintenance requirements but may have others instead.

One reason for the ICE's success is the high energy density of the fuels it uses. Gasoline and diesel are fantastically dense carriers of energy, which gives today's ICEVs ranges limited primarily by the driver rather than any technical limitation. A typical car might have a range of 500 miles and a truck 1000 miles. This equates to 10 h of driving time for a car and 20 h for a truck, assuming an average speed of 50 MPH.

The high energy density of liquid fuels not only enables long vehicle range, but also fast energy transfer. In a gasoline refueling station (gasoline LHV = 32.3 MJ/L [42]), assuming a car is filled at 50 LPM, the resulting power (energy transfer rate) is approximately 27 MW. In a heavy-duty diesel refueling station (diesel LHV = 36.0 MJ/L [42]), assuming a truck is filled at 150 LPM, the resulting power is approximately 90 MW. Tesla's Supercharger network, marketed as the world's fastest electric vehicle charging network, offers a power of "up to" 150 kW [43]—at least two orders of magnitude slower than liquid fuels.

The ICE is supported by a comprehensive and extensive global infrastructure network, from refueling stations to mechanics workshops. In addition, today's ICE vehicles are very reliable. Manufacturer guarantees now extend up to seven years or 100,000 miles—a significant portion of a vehicle's expected lifetime [44].

Finally, as an established and well-developed technology, ICEs are remarkably low cost—typically making up less than 10% of the total cost to manufacture a vehicle [45]. All of these factors have led to the ICE being the dominant propulsion technology today. At the moment, there is little or no cost associated with discarding CO_2 and pollutant emissions from ICEs. Until these costs are substantial, which could come at a high political price, the ICE is likely to retain its dominant role in mobility.

Real Driving Emissions (RDE)

European legislation has mandated RDE testing for vehicles since September 2017 with the introduction of the Euro 6d-Temp legislation. This means that, for the first time in legislation, vehicle emissions are tested on the road in real traffic conditions. The intention of this legislation is to reduce "cycle beating" approaches and to close the gap between real emissions and emissions over the certification drive cycles. Therefore, in the EU, modern ICEVs are being certified to very strict standards for pollutant emissions both in the lab *and* on the road.

In addition, independent RDE tests reveal that many modern vehicles, both gasoline and diesel, can emit near-zero levels of pollutant emissions. Emissions Analytics, a consulting company, has a wide, publicly available database of independent RDE tests [46]. They tested 840 gasoline and diesel vehicles (at the time of writing) from model year 2009 and found that 46% emit less than 60 mg/km NO_x—the Euro 6 gasoline limit implemented six years later in 2015. ADAC, the German automobile association, conducted a similar set of tests in 2019 (again testing both gasoline and diesel vehicles) and found that all but two emitted less than 50 mg/km NO_x, with the Mercedes C220d emitting effectively 0 mg/km [47].

The low emissions from these vehicles are due to extremely effective exhaust aftertreatment systems, which can have almost 100% efficacy at removing pollutants. This data shows that in real driving conditions, it is possible for ICE vehicles to emit zero (or below a measurable threshold) pollutant emissions (*i.e.*, everything but CO_2 and water). This is not a future promise; these are real vehicles, in independent tests, available to buy today.

Advancements in internal combustion engines and their fuels

A common misconception is that ICEs have not changed in the last 100 years. On the contrary, combustion systems have significantly improved, with an over 90% increase in average fuel economy between 1975 and 2015 [48]. Similarly, exhaust emissions (particulates, NO_x, CO, and unburned hydrocarbons) have undergone a 1000-fold reduction over the last four decades [49]. These improvements have occurred alongside significant enhancements in performance. Indeed, over the last 45 years, a combination of government regulations and technology innovation has led to significant progress in the development of cleaner and more efficient engines. The progress has been remarkable, but with stringent future regulations in place, there is much more work to do. Fortunately, advanced engine concepts and low-carbon fuels can help us meet these targets.

Advanced engine concepts

There is significant untapped potential in advanced ICE concepts, which have been recently reviewed in Refs. [4,50]. For example, concepts such as gasoline compression ignition (GCI) and reactivity controlled compression ignition (RCCI) have been shown to achieve diesel-like efficiencies with very low soot and NO_x emissions.

Table 2, with data from Ref. [4], shows a number of advanced engine technologies and compares their CO_2 reduction potential to a baseline turbocharged gasoline direct injection (GDI) engine design. Concepts such as lean-burn GDI, dedicated EGR, GCI, RCCI, and two-stroke opposed piston can offer a significant reduction in CO_2 emissions compared to the baseline. This does not come without challenges, however, which are also addressed in Ref. [4].

Low-carbon fuels

Although the majority of today's engines are fueled from fossil-derived sources, this need not necessarily be the case. The source of the required blend of hydrocarbons is immaterial to the engine, and there are ways of synthesizing the hydrocarbons while avoiding fossil sources. These paths enable the production of fuels that are carbon free or lower carbon than fossil-derived fuels. There are two common categories of low-carbon fuels: biofuels and e-fuels.

One advantage of low-carbon fuels is that they can be used with the existing fleet. The average age of vehicles on the road in the US is 12 years old [51]; in Europe, 11 years old [52]; and the average age of an imported (*i.e.*, new to the customer) vehicle in Uganda is 16 years old [53]. Unless fleet renewal is globally subsidized at high levels (through scrappage schemes, for example) many of today's new vehicles are likely to be on the road until the 2040s. The only way to decarbonize this transportation is through low-carbon fuels that are compatible with the existing fleet. This also has the advantage of avoiding embedded carbon associated with manufacturing new vehicles.

A recent analysis from Ricardo [54] explored three scenarios to meet an EU target of 85% CO_2 reduction by 2050. This analysis concluded that for the fastest and most cost-effective CO_2 reduction, low-carbon fuels, alongside a mixed electrified fleet (including BEVs, MHEV, FHEV, and PHEVs) were essential. Pure BEV scenarios suffered from availability of scarce resources as well as higher cost and slower adoption. An alternative analysis by FEV showed similar results [55].

Biofuels. Biofuels hold great potential for decarbonizing future mobility. This type of fuel is produced from biomaterial (*e.g.*, from a plant) that has formed its carbonaceous structure from atmospheric CO_2. Ethanol, made typically from wheat or sugar beet, is the most popular biofuel component for gasoline. Fatty-acid-methyl-ester (FAME) components are the most common biodiesels and are usually sourced from vegetable oils and animal fat. In theory, a biofuel can be carbon-neutral provided that any biomaterial harvested to create the fuel is replanted. In practice, there are

Table 2
Overview of advanced engine technologies and their CO_2 reduction potential. Data from Joshi [4].

Engine Technology	CO_2 Reduction Potential
Baseline: GDI, turbo, stoichiometric	0
Atkinson cycle (+VVT)	3–5%
Advanced start-stop	2–5%
Dynamic cylinder deactivation + Mild hybrid or Miller cycle	10–15%
Lean-burn GDI	10–20%
Variable CR	10%
GCI	15–25%
Water Injection	5–10%
Homogeneous Lean	15–20%
Dedicated EGR	15–20%
RCCI	20–30%
Two-stroke opposed piston diesel	25–35%

a number of confounding factors, including carbon emissions associated with land-use change and concerns about ensuring food supply. In addition, the CO_2 associated with the production and transportation of the biofuels needs to be accounted for. Nevertheless, there is significant potential for biofuels to reduce CO_2 emissions from transportation in a cost-effective manner [56,57].

Despite concerns about the true carbon intensity of first-generation biofuels [58], the latest developments, particularly with ethanol, have dramatically reduced their carbon intensity, as shown in Fig. 1. In addition, biofuels produced from micro-algae have a low carbon intensity as well as no impact on land use for food production [59].

There are synergistic benefits to the use of oxygenate components in gasoline, notwithstanding the potential renewable nature of these components [61,62]. For example, the "Co-Optima" initiative in the US [63] has suggested that alcohol fuels such as ethanol or propanol can be used to further increase ICE efficiency and reduce engine-out CO_2 emissions [64]. Notably, Sluder [64] found that engine efficiency (and fuel economy) increases of 2–10%, as well as similar reductions in tailpipe CO_2 emissions, were possible with a variety of different oxygenate components. This was achieved while retaining fuels that were within ASTM distillation specifications for wintertime fuel blends (which are a limiting factor for the current fleet due to some oxygenate components' poorer "cold start" performance).

There are other potential synergistic benefits to having fuels with bio-content, for example, being able to reform the fuel onboard to enable octane-on-demand for the highest efficiency [65]. Octane-on-demand is a system where a high-octane and low-octane fuel can be alternated according to need to obtain peak engine efficiency (*i.e.*, use a high-octane fuel only when knock-limited). However, such additional complexity, particularly requiring a customer to fill up their vehicle with two fuels, is not popular. Ethanol provides a way of offering octane-on-demand without requiring two fuels through on-board reformation. In a study that included passenger cars and a light goods vehicle, Kasseris et al. noted fuel economy improvements of 20–30% with such a system, while only needing to fill a single tank with standard E10 gasoline [65]. Combining biofuels with GCI is also being explored for synergisms [66].

The EU has been implementing biofuel policy since 2003 [67] with the aim that the road transport fuel mix should be 6% less carbon intensive than pure fossil in 2020. E5 (a blend of gasoline containing 5% ethanol by volume) and B7 (a blend of diesel containing 7% FAME by volume) have been widespread for over a decade. In the US, E10-E15 is common for gasolines, as well as E85, which requires so-called flex-fuel vehicles. In both markets there have been various incentives to promote the uptake of biofuels.

In the short term, increased ethanol content in both US and European gasoline is likely. The US EPA recently announced that E15 fuels will be permitted year round [68]. The EU is actively investigating E20 fuels [69]. Due to its lower volumetric energy density compared to gasoline, E5 increases fuel consumption by about 1.5% and higher blends in proportion. Nevertheless, increases in ethanol concentration are a pathway to increased efficiency and reduced CO_2, which is proven to be cost-effective and acceptable to consumers.

E-fuels. Another potential route towards decarbonizing transportation includes fuels that can be made from CO_2, so-called "e-fuels" (sometimes referred to as power-to-liquid (P2L)) [70]. In theory, by reforming CO_2 over catalysts, liquid fuel can be made directly from CO_2. The CO_2 could be sourced either from a CO_2-rich exhaust (*e.g.*, from a power plant) or extracted directly from the atmosphere. If the energy-intensive manufacturing process uses renewable energy, the fuel is CO_2 neutral, since any CO_2 emitted by combusting the fuel has been extracted from the atmosphere in its manufacture [71].

Theoretically any hydrocarbon fuel could be manufactured this way. Currently, components such as oxymethylene ether and octanol, both diesel replacements, and methanol, a gasoline replacement, are a major focus due to their relative economy in being produced. However, this is a fast developing area and the focus may shift in the near future. Another method, the Fischer-Tropsch process, can be used to obtain long-chain, saturated hydrocarbons more similar to fossil fuels [72].

Methanol can be synthesized either as a biofuel or an e-fuel [73]. Its use in ICEs has been widely evaluated in various blending levels [74]. Methanol has been used as a fuel in China for some time [75], where it has typically been synthesized from coal, and its use, today in a renewable form, is being promoted [76].

While e-fuels offer an option for zero carbon mobility, it is not clear that they will provide the most efficient solution either economically or in terms of energy usage. They do not suffer from the "food or fuel" concern that biofuels do; however, with an overall efficiency of 13% (compared to 22% for a fuel cell and 73% for a BEV), their use might be restricted to applications where the energy density of liquid hydrocarbons is essential, for example, long-distance road transportation or aviation [77].

Efficiency potential

Today, peak gasoline engine efficiency is around 40% for light-duty vehicles [37], and light-duty diesel vehicles have peak efficiencies

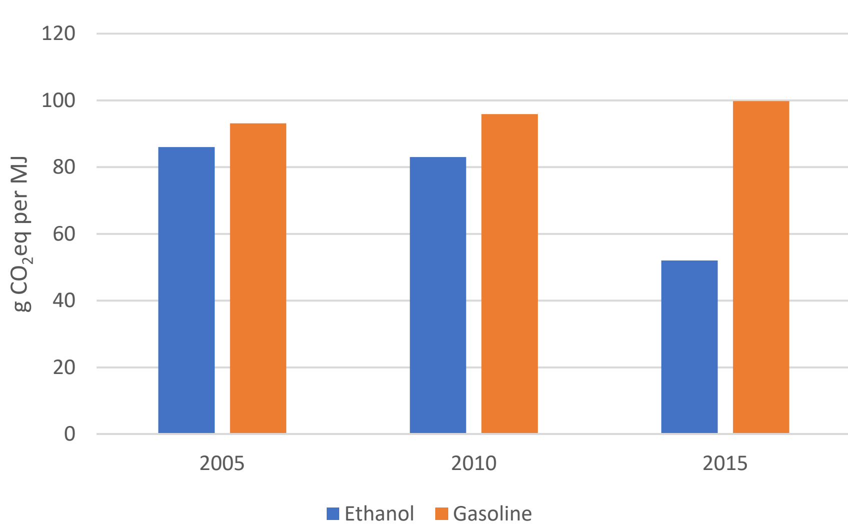

Fig. 1. Relative CO_2 intensities of ethanol and gasoline 2005–15. Data from Ref. [60].

around 43% [38]. Heavy-duty diesel engines have higher peak efficiencies of around 47% due to their superior surface-area-to-volume ratios [78]. Marine engines have still more favorable surface-area-to-volume ratios and low engine speeds, so they operate with even lower heat losses. As a result, marine engine efficiencies are higher than road transport engines, with Wärtsilä releasing its W31 engine with a >50% efficiency in 2016 [79]. The advances in marine engine efficiency are shown in Fig. 2.

The US DoE SuperTruck II program aims to demonstrate a heavy-duty 55% engine brake thermal efficiency by 2022 [80]. Looking further ahead, prototype split-cycle engines, showing 60% thermal efficiency, are being built. These engines look feasible for stationary power generation applications in the short term and heavy-duty transport applications subsequently [81,82].

Energy balance studies on ICEs show that the majority of energy losses are due to heat losses and exhaust enthalpy, mostly the heat of the engine exhaust [83,84]. As a result, efforts to minimize heat loss using temperature swing coatings, which attempt to match wall and gas temperatures, are a focus of research today, with some coatings already being deployed [85]. Similarly, exhaust enthalpy recovery, using the Brayton cycle, for example, is also being explored [86].

With many efforts focused on increasing engine efficiency, it is pertinent to ask, “where is the limit?” Otto cycle efficiency is limited by compression ratio (CR) and the ratio of specific heats. Therefore, assuming a CR of 100 and a gamma of 1.3, 75% efficiency is possible. More practical limitations indicate that a CR of 50 could result in a gasoline engine efficiency in excess of 60% [87]. Mixed ICE/fuel cell systems have been theoretically shown to have efficiencies up to 70% [88]. Thus, there is substantial room for improvement in ICE efficiency.

Battery electric vehicles

Of course, BEVs also continue to advance. One advantage of BEVs is that they have no tailpipe—there are no exhaust emissions nor GHGs coming from the car itself. As a result, local air quality may be improved through the use of fully electric vehicles. But truly determining the environmental impact of any transportation system requires one to look at the system as a whole throughout its lifetime.

Perhaps the most obvious source of GHGs from a BEV is the electricity used to charge the battery. Where does this electricity come from? It comes from a variety of sources, which is another benefit of BEVs—we can make electricity in different ways, reducing our dependence on any single source. However, in much of the world, a substantial portion of electricity is generated from fossil fuels, namely coal and natural gas. As of 2017, about 67% of the world's electricity comes from combustible fuels [89]. Nevertheless, the hope is that as more electricity is produced from renewable sources, GHGs from vehicle charging will be significantly reduced. Given the current numbers, however, we have a long way to go.

While BEVs have no *exhaust* particulate emissions, their *non-exhaust* PM tends to be higher than conventional vehicles due to their increased weight. Timmers and Achten have shown that a positive relationship exists between vehicle weight and non-exhaust emissions—increased weight results in increased PM from tires, brakes, and road surfaces. As a result, total PM emissions from BEVs and ICEVs are comparable [90].

Another significant source of GHG emissions in BEVs comes from battery production. Qiao et al. [13] compared the cradle-to-gate (not to be confused with cradle-to-grave) GHG emissions of a standard mid-sized passenger ICEV and a BEV in the context of China. All processes, including material production, component production and assembly, and energy transformation, were considered. GHG emissions were identified as CO_2, CH_4 and N_2O and converted to CO_2eq. It was found that the CO_2eq values are about 50% higher for a BEV compared to an ICEV. This is mainly due to battery production and the increased use of steel in BEVs. The greater weight of a BEV in general results in larger GHG emissions from several components compared to an ICEV [13]. Other studies have shown similar results. For example, Hao et al. studied the three types of most commonly used lithium-ion batteries (LFP, NMC, and LMO) and found around a 30% increase in GHG emissions in China from electric vehicle production compared with conventional vehicles [91].

Hawkins et al. showed that the global warming potential (GWP) from EV production in Europe is roughly twice that associated with ICEV production [92]. Vidhi and Shrivastava examined the policy and behavioral changes that will be required if India is to adopt the goal of selling 100% EVs by 2030. They found that emissions during battery manufacturing would negate any savings achieved by EVs, unless India's electricity generation source changes significantly [93].

Clearly, only considering tailpipe emissions misses a significant portion of GHG production. When comparing different transportation technologies, a total life-cycle analysis (LCA) should be considered. Assuming a 150,000 km vehicle lifetime, Hawkins et al. determined that BEVs powered by coal electricity would cause an increase in GWP of 17% and 27% compared with gasoline and diesel ICEVs, respectively. Using the actual European electricity mix results in only a 10–14% reduction in LCA GWP for BEVs compared to diesel ICEVs and a 20–24% reduction compared to gasoline ICEVs [92]. In a report by A.D. Little, it was concluded that ICEVs have a lower GWP impact in the first 3–4 years of operation compared to equivalent BEVs for new cars produced between 2015 and 2025 [94].

Kawamoto et al. [95] calculated the life-cycle CO_2 emissions for BEVs and ICEVs, taking into consideration the vehicle's lifetime driving distance for five different regions: the EU, Japan, the US, China, and Australia. In each region, they determined the “distance of intersection point” or DIP. This is

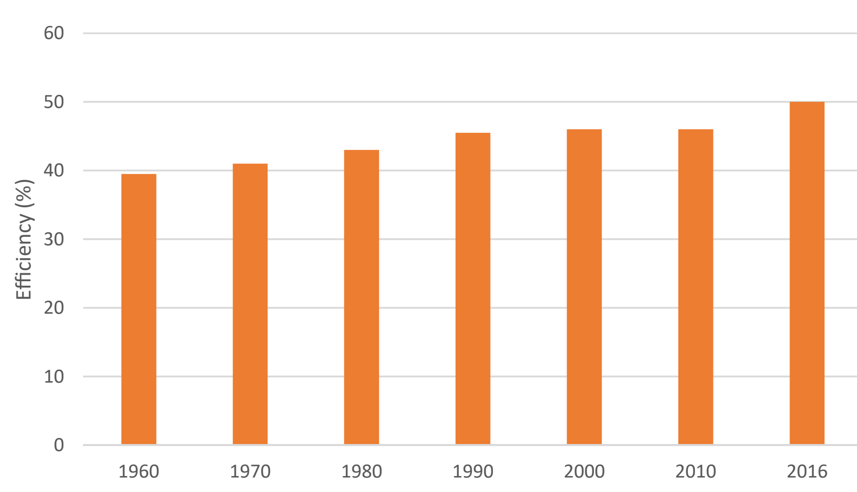

Fig. 2. Wärtsilä engine efficiency from 1960 to 2016. Data from Ref. [79].

the distance, in kilometers driven, when the life-cycle CO_2 emissions crosses over between BEVs and either gasoline or diesel ICEVs. In all regions, the CO_2 at 0 km (*i.e.*, the CO_2 from vehicle production) is significantly higher for a BEV compared to gasoline or diesel engine vehicles. The DIP's are shown in Table 3. The calculations assumed that the battery of a BEV would be replaced once at 160,000 km. As can be seen in the table, ICEVs have lower life-cycle CO_2 compared to BEVs in all regions for both fuels for driving distances less than 60,779 km (the US gasoline-BEV DIP value). If we assume an average driving distance of 20,000 km/year, this corresponds to more than three years of driving. This number goes as high as 119,104 in China, corresponding to almost six years of driving. In Australia, there is no intersection distance, meaning the CO_2 from a BEV is always higher than an ICEV. Finally, in multiple regions, a second intersection point occurs at 160,000 km (about 8 years of driving) when the BEV lifetime CO_2 once again goes above the ICEV CO_2. Even in the best case scenario (lowest value of DIP in [] with no second intersection point) which occurs in the US, the end of life CO_2 of the BEV is 20% lower than the ICEV [95]. While this is a substantial savings, it is a far cry from the "zero carbon" tag often placed on BEVs.

Wu et al. took a region-based LCA approach even further by comparing technologies down to the US county level. They found that regional differences in climate, electric grid, and driving habits result in significant regional heterogeneity in emissions benefits of a particular technology. Their results suggest that an aluminum lightweight ICEV has similar emissions to FHEVs in about 25% of US counties. These same ICEVs have lower emissions than BEVs in over 20% of US counties [96].

Hawkins et al. studied a wide range of impacts of BEVs and ICEVs in addition to GWP. It was found that different BEV options have 180–290% greater human toxicity potential (HTP) impacts compared to ICEVs, primarily from the additional copper requirements of BEVs [92]. A.D. Little had a similar finding, with a roughly 200% increase in HTP impacts in BEVs over ICEVs in 2015, with this difference increasing by 50% through 2025 [94]. They concluded that "… BEVs and ICEVs both represent a complex set of economic and environmental trade-offs, in which advancements in one area are unavoidably connected to impacts in another. All of these trade-offs must be considered holistically …" [94].

In an invited review paper for the British Medical Bulletin, Jones asked the question "If electric cars are the answer, what was the question?" [97]. Jones looked at everything from road traffic injuries to air pollution, and concluded that "Overall, the negative health consequences of electric cars seem likely to be at least those of internal combustion engine cars" [97].

Add to this range anxiety, charge time, infrastructure, battery decommissioning, and the need to mine rare materials, and it becomes apparent that BEVs are far from the single solution to our transportation problem.

The case for hybrids

Hybridization offers a number of benefits. First, energy recovery during vehicle braking is straightforward, so much of the fuel energy that is wasted in brakes in an ICEV can be recovered and reused, leading to greater energy efficiency and lower CO_2 emissions. Some hybrid configurations allow for limited ICE operating points, such that the ICE will run where it is most efficient, which, again, reduces CO_2 emissions. ICEs can be switched off when not needed (*e.g.*, for deceleration and idling/hoteling events). Many hybrid configurations allow for EV-only operation for a limited distance. So, for example, PHEVs could be "geofenced" such that they operate in pure electric mode in low-emissions zones (such as a polluted city center) and then use the ICE outside of these zones. This could quickly improve urban air quality in a way that is feasible in the near future.

Table 3
Distance of intersection point (DIP) values for gasoline-BEV and diesel-BEV combinations in five different regions (data from Ref. [95]). Values in [] indicate the distance where the lifetime CO_2 of the ICEV surpasses the BEV. Values in {} indicate where the CO_2 of the BEV again goes above the ICEV. Note that Diesel-BEV DIP values were only calculated for the EU and Japan.

Region	Gasoline-BEV DIP (km)	Diesel-BEV DIP (km)
EU	[76,545]	[109,415], {160,000}
Japan	[111,511], {160,000}	[114,574], {160,000}
US	[60,779]	NA
China	[119,104], {160,000}	NA
Australia	{No intersection}	NA

Hybrids can come in a number of configurations. MHEVs store energy recovered during braking in a battery and use it for acceleration assistance. FHEVs do the same and add the ability to charge the battery through the ICE. PHEVs allow external electricity to be used to charge the battery and typically have larger batteries as a result. Hybrid systems can have serial, parallel, or power-split configurations. In serial configurations, electric motors always drive the wheels, and the ICE produces power either to charge the battery or directly to the electric motors through a generator. In this configuration, the engine can run at a predetermined RPM where it is most efficient. On the other hand, in parallel configurations, either the electric motors or the ICE can drive the wheels. Typically, the ICE powers the wheels at higher speeds where it is the most efficient. The power-split system, which is used in the Toyota Prius, for example, combines the parallel and series configuration through a planetary gearbox. By combining configurations, hybrid powertrains allow for maximum efficiency, power, and driving comfort.

Hybrids are the fastest way to reduce CO_2 emissions from vehicles

BEVs need large batteries. For example, a Nissan LEAF with 239 mile range has a 62 kWh battery [98]. Batteries are a scarce resource; at the start of 2019, global battery production capacity was 286 GWh per year and is forecast to reach 1000 GWh per year by 2023 [99]. Nearly quadrupling battery production infive years is aggressive, but assuming it is met, it equates to annual production needs for 20 million BEVs with an average battery size of 50 kWh. In 2018, over 70 million cars and 21 million light commercial vehicles were produced [100]. Therefore, even aggressive projections show that in 2023, battery capacity will allow only 29% of new cars to be BEVs (and significantly fewer if the cars use larger, longer range batteries), assuming no light commercial vehicles are BEVs.

In addition, CO_2 reduction benefits are non-linear. In other words, moderate electrification (*i.e.,* FHEV) has a significant benefit, but further benefit reduces for full BEVs. Therefore, given the limited resources, it would be expected that putting a small battery in every car would result in a greater overall CO_2 reduction than putting large batteries in fewer cars.

A recent study by Emissions Analytics [101] tested 95 hybrid vehicles. On average these hybrids had a 1.2 kW battery and delivered a 30% reduction in CO_2 emissions relative to current ICE vehicles. The EU has a post-2021 CO_2 reduction target for passenger cars of 37.5% by 2030, so current hybrids could achieve 75% of that without further development. Of course, further development *is* happening. For example, the 2020 Ford Escape hybrid (1.1 kWh battery and a 4 cyl 1.5 L Ecoboost engine) has 50% lower CO_2 emissions compared to the 2019 Ford Escape [102].

The overall CO_2 reduction per unit battery size according to Emissions Analytics is shown in Table 4. Each hybrid is compared with its nearest equivalent ICE-only vehicle. The analysis is on a tailpipe basis (*i.e.*, a BEV emits 0 CO_2) and ignores any CO_2 emissions associated with the battery, electricity generation, and fuel production, which is likely to further benefit the FHEV relative to the BEV. As shown, MHEVs and FHEVs result in significantly higher CO_2 reduction per unit battery size compared to PHEVs and BEVs.

A similar study by Joshi [103] that takes into account some life-cycle analysis, including the CO_2 emissions associated with the battery, electricity generation, and fuel production, showed that an FHEV had an approximately 20% reduction in CO_2 emissions relative to an ICEV, with a further 18% reduction (on average) possible with a BEV. However, the lowest-emitting hybrids emit the same CO_2 over their life (defined as 150,000 km/10 years) as the best BEVs.

Hybrids are the fastest way to decarbonization given the likely limited supply of batteries over the next decade, the rapid developments in hybrid technology, and the ICE improvements that are already entering production. In addition, Elgowainy et al. found that hybrids offer the most appealing cost in terms of avoided carbon emissions [104]. In their study, the expected future (2025–2030) cost and GHG emission of several vehicle technologies, including ICEVs, FHEVs, PHEVs, and BEVS, were analyzed and compared to a conventional gasoline engine vehicle. FHEVs and PHEVs were found to result in the lowest cost per CO_2eq avoided, further supporting the use of hybrids in the future fleet.

Challenges for hybridization

As vehicles become more hybridized, the combustion engine will need to evolve. The engine will be part of a powertrain system that includes a significant level of electrical power. While engines have always been a part of systems (*e.g.,* the transmission), the demands on the ICE are likely to change. For example, the ICE will not be switched on at all times, it may not need to operate at such a wide range of loads and speeds, and there will be electric motors to help with transients and possibly electrical aftertreatment heating. Future combustion engines may thus be smaller and cheaper. As an example, the BMW i3 PHEV has a 2-cylinder, 647 cc engine, whereas comparable "B segment" vehicles might have a 1.6 L 4-cylinder engine. In addition, the added complexity of having two drivetrains is an engineering challenge that needs to be considered.

Consumer behavior must also be addressed as we develop future mobility systems. A study by the Miles Consultancy found that many drivers of PHEVs had never charged their vehicles with the plug [105]. To obtain the reduced CO_2 emissions promised by PHEVs, they must be used as plug-in vehicles. However, due to a lack of infrastructure or lack of convenience, customers have not treated them as such. Using PHEVs in this manner results in greater CO_2 emissions compared to an FHEV or MHEV alternative, since the PHEVs are carrying around redundant batteries.

This problem may be partially mitigated as more infrastructure is created for charging EVs. However, the problem is also a branding one. Consumers assume that PHEVs are better for the environment than FHEVs or MHEVs in all scenarios simply because they are more electrified, which, as discussed above, is not necessarily the case. For certain consumers, FHEVs and MHEVs will result in lower emissions, and they should be made aware of this fact. However, consumers should also not be misled by branding. For example, standard ICE-powered vehicles equipped with stop-start are being marketed as "micro-hybrids" [106] and FHEVs are being described as "self-charging electric vehicles" or "self-charging hybrids" [107]. Such branding can overcome perception problems, but it is important that consumers are not misled. Customers must be informed and engaged, and solutions that consumers are willing to adopt must be engineered and developed.

Recommendations and conclusions

In light of the data presented in this paper, we make the following recommendations which we hope will be considered by policymakers and auto manufacturers now and in the future:

1. Take a balanced approach to transportation, recognizing that there is no silver bullet solution.
2. Do not ban any particular technology. Set targets and let the best technology win, understanding that the best technology will likely vary depending on region.
3. Use LCA when comparing technologies. Including only the tailpipe emissions, or even the "use phase" can significantly misrepresent a technology's environmental impact.
4. Continue to invest in ICE technology for three reasons: a) there is much untapped potential to still exploit; b) ICEs are going to be present in electrified vehicles for years to come; and c) if we cease to invest in ICEs, there is danger that we will lose the opportunity to improve the technology, which would prove especially problematic if electric cars do not meet expectations.
5. Devote significant resources to investigating carbon-neutral fuels. Success in this area will not only allow us to lower emissions in the current fleet, but it will also make use of much of the current infrastructure.
6. Hybrids are the fastest way to reduce CO_2 emissions from vehicles. They should be treated as such.
7. Engineering—not politics—should drive future transportation policy.

Table 4
CO_2 emissions reduction comparison between hybrids and BEVs (data from Ref. [101]).

Vehicle type	Average CO_2 reduction (g/km)	CO_2 reduction per unit battery size (g/km/kWh)
MHEV	25	73.9
FHEV	65	50.5
PHEV	126	12.0
BEV	210	3.5

Further developing the internal combustion engine, along with various levels of electrified approaches, allows consumers to choose the technology that best suits their needs. This balanced and diversified approach is, in our opinion, the most pragmatic way to substantially reduce the environmental impact of transportation.

Conflict of interest

Authors declare that they have no conflict of interest.

Acknowledgements

The authors would like to thank Elizabeth Berge Favreau for her extensive help in researching and editing this work.

Nomenclature

BEV	Battery electric vehicle
CCGT	Combined cycle gas turbine
CO_2eq	Carbon dioxide equivalent
CR	Compression ratio
DIP	Distance of intersection point
EGR	Exhaust gas recirculation
EV	Electric vehicle (BEVs and PHEVs)
FAME	Fatty-acid-methyl-ester
FHEV	Full hybrid electric vehicle
GCI	Gasoline compression ignition
GDI	Gasoline direct injection
GHG	Greenhouse gas
GWP	Global warming potential
HTP	Human toxicity potential
ICE	Internal combustion engine
ICEV	Internal combustion engine vehicle
LCA	Life-cycle analysis
LHV	Lower heating value
MHEV	Mild hybrid electric vehicle
OME	Oxymethylene ether
PHEV	Plug-in hybrid electric vehicle
PM	Particulate matter
RCCI	Reactivity controlled compression ignition
RDE	Real driving emissions

References

[1] How many cars are there in the world?, CarsGuide. https://www.carsguide.com.au/car-advice/how-many-cars-are-there-in-the-world-70629 (Accessed 13 October 2019).
[2] D.A. King, M.J. Smart, M. Manville, The poverty of the carless: toward universal auto access, J. Plan. Educ. Res. (2019), https://doi.org/10.1177/0739456X18823252, 0739456X18823252.

[3] H. Ritchie, M. Roser, CO_2 and greenhouse gas emissions, our world in data. https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions, 2017. (Accessed 13 October 2019).
[4] A. Joshi, Review of vehicle engine efficiency and emissions, 2019-01–0314, https://doi.org/10.4271/2019-01-0314, 2019.
[5] R. Hotten, Volkswagen: the Scandal Explained, BBC News, 2015. https://www.bbc.com/news/business-34324772. (Accessed 13 October 2019).
[6] Worldwide sales of Toyota hybrids surpass 10 million units, worldwide sales of Toyota hybrids surpass 10 million units. https://newsroom.toyota.eu/global-sales-of-toyota-hybrids-reach-10-million/ (Accessed 13 October 2019).
[7] D. Barthmuss, Who ignored the facts about the electric car?. http://www.altfuels.org/misc/onlygm.pdf, 2006.
[8] L. Thomas, Elon Musk: We Started Tesla after Big Auto Companies Tried to "Kill" the Electric Car, CNBC, 2017. https://www.cnbc.com/2017/06/09/elon-musk-i-started-tesla-after-detroit-tried-to-kill-electric-cars.html. (Accessed 13 October 2019).
[9] J. Pontes, EV sales: global top 20 - december 2018, EV sales. http://ev-sales.blogspot.com/2019/01/global-top-20-december-2018.html, 2019. (Accessed 13 October 2019).
[10] Tesla net income 2009-2019 | TSLA. https://www.macrotrends.net/stocks/charts/TSLA/tesla/net-income (Accessed 13 October 2019).
[11] News Analysis: China mulls fossil fuel car ban, boosts electric vehicles - xinhua | English.news.cn. http://www.xinhuanet.com/english/2017-09/13/c_136606474.htm (Accessed 13 October 2019).
[12] D. Sandalow, Guide to Chinese Climate Policy 2018, Center on Global Energy Policy, Columbia School of International and Public Affairs, 2018. https://energypolicy.columbia.edu/sites/default/files/pictures/Guide%20to%20Chinese%20Climate%20Policy%207-27-18.pdf.
[13] Q. Qiao, F. Zhao, Z. Liu, S. Jiang, H. Hao, Cradle-to-gate greenhouse gas emissions of battery electric and internal combustion engine vehicles in China, Appl. Energy 204 (2017) 1399–1411, https://doi.org/10.1016/j.apenergy.2017.05.041.
[14] Costa Rica to ban fossil fuels and become world's first decarbonised society, the Independent. https://www.independent.co.uk/environment/costa-rica-fossil-fuels-ban-president-carlos-alvarado-climate-change-global-warming-a8344541.html, 2018. (Accessed 13 October 2019).
[15] U. Irfan, Costa rica has an ambitious new climate policy — but no, it's not banning fossil fuels, Vox. https://www.vox.com/energy-and-environment/2018/7/17/17568190/costa-rica-renewable-energy-fossil-fuels-transportation, 2018. (Accessed 13 October 2019).
[16] France to uphold ban on sale of fossil fuel cars by 2040, Reuters. https://www.reuters.com/article/us-france-autos-idUSKCN1TC1CU, 2019. (Accessed 13 October 2019).
[17] S. Szymkowski, Denmark to EU: ban sale of internal-combustion engine cars come 2040, Roadshow. https://www.cnet.com/roadshow/news/denmark-eu-ban-gas-diesel-cars/ (Accessed 13 October 2019).
[18] "Internal combustion engines, EV-based automobiles can co-exist": SIAM welcomes PM Modi's assurance - times of India, the Times of India. https://timesofindia.indiatimes.com/auto/miscellaneous/internal-combustion-engines-ev-based-automobiles-can-co-exist-siam-welcomes-pm-modis-assurance/articleshow/70674679.cms (Accessed 13 October 2019).
[19] Decarbonization Plan, Government of Costa Rica. https://www.2050pathways.org/wp-content/uploads/2019/02/Decarbonization-Plan-Costa-Rica.pdf, 2019.
[20] Denmark's draft integrated national energy and climate plan, energi-, forsynings- og klimaministeriet. https://ens.dk/sites/ens.dk/files/EnergiKlimapolitik/denmarks_draft_integrated_energy_and_climate_plan.pdf, 2018.
[21] Climate Plan: 1 Planet, 1 Plan, Ministère de la Transition écologique et solidaire, France. https://franceintheus.org/IMG/pdf/climate_plan_-_press_pack_1.pdf, 2017.
[22] A. Ghoshal, Watch: India Unveils Ambitious Plan to Have Only Electric Cars by 2030, India Edition, International Business Times, 2017. https://www.ibtimes.co.in/watch-india-unveils-ambitious-plan-have-only-electric-cars-by-2030-724887. (Accessed 13 October 2019).
[23] Climate Action Plan 2019, Government of Ireland, 2019. https://static.rasset.ie/documents/news/2019/06/climate-action-plan.pdf.
[24] S. Solomon, Israel aims to eliminate use of coal, gasoline and diesel by 2030. https://www.timesofisrael.com/israel-aims-to-eliminate-use-of-coal-gasoline-and-diesel-by-2030/ (Accessed 13 October 2019).
[25] Israel aims for zero new gasoline, diesel-powered vehicles by 2030, Reuters. https://www.reuters.com/article/us-israel-electric-vehicles-idUSKCN1MJ1PS, 2018. (Accessed 13 October 2019).
[26] Draft Integrated National Energy and Climate Plan 2021-2030, 2018. The Netherlands, https://ec.europa.eu/energy/sites/ener/files/documents/netherlands_draftnecp_en.pdf.pdf.
[27] National Transport Plan 2018-2029, Norwegian Ministry of Transport and Communications, 2018. https://www.regjeringen.no/contentassets/7c52fd2938ca42209e4286fe86bb28bd/en-gb/pdfs/stm201620170033000engpdfs.pdf.
[28] UK Plan for Tackling Roadside Nitrogen Dioxide Concentrations: an Overview, UK Government, 2017. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/633269/air-quality-plan-overview.pdf.
[29] UK Plan for Tackling Roadside Nitrogen Dioxide Concentrations: Detailed Plan, UK Government, 2017. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/633270/air-quality-plan-detail.pdf.
[30] R. och, Regeringskansliet, Statement of Government Policy, 21 January 2019, Regeringskansliet, 2019. https://www.government.se/speeches/20192/01/statement-of-government-policy-21-january-2019/. (Accessed 13 October 2019).
[31] Volvo Cars to go all electric. https://www.media.volvocars.com/global/en-gb/media/pressreleases/210058/volvo-cars-to-go-all-electric (Accessed 13 October 2019).
[32] Volvo Goes Electric across the Board, BBC News, 2017. https://www.bbc.com/news/business-40505671. (Accessed 13 October 2019).
[33] R. Irle, Global EV sales for 2018 - final results, EV-volumes.com. http://www.ev-volumes.com/news/global-ev-sales-for-2018/ (Accessed 13 October 2019).
[34] What cars will we be driving in 2050?, Fuel Freedom Foundation. https://www.fuelfreedom.org/cars-in-2050 (Accessed 13 October 2019).
[35] N. Bomey, Old cars everywhere: average vehicle age hits all-time high, USA TODAY. https://www.usatoday.com/story/money/cars/2019/06/28/average-vehicle-age-ihs-markit/1593764001/ (Accessed 13 October 2019).
[36] Monitoring CO2 Emissions from New Passenger Cars and Vans in 2016, European Environment Agency. https://www.eea.europa.eu/publications/co2-emissions-new-cars-and-vans-2016 (Accessed 13 October 2019).
[37] J. Kargul, M. Stuhldreher, D. Barba, C. Schenk, S. Bohac, J. McDonald, P. Dekraker, J. Alden, Benchmarking a 2018 Toyota camry 2.5-liter atkinson cycle engine with cooled-EGR, SAE Int. J. Adv. & Curr. Prac. in Mobility. 1 (2019) 601–638, https://doi.org/10.4271/2019-01-0249.
[38] S. Busch, K. Zha, Analysis of Efficiency Improvements in a Light-Duty Diesel Engine with a Stepped-Lip Piston, Sandia National Lab. (SNL-CA), Livermore, CA (United States), 2016. https://www.osti.gov/biblio/1375296. (Accessed 13 October 2019).
[39] A. Bejan, Thermodynamics Today, Energy, vol. 160, 2018, pp. 1208–1219, https://doi.org/10.1016/j.energy.2018.07.092.
[40] MHPS, Record-breaking efficiency. https://amer.mhps.com/j-series.html (Accessed 13 October 2019).
[41] J. Doward, New Law to Tackle Electric Cars' Silent Menace to Pedestrians, The Observer, 2018. https://www.theguardian.com/environment/2018/may/06/new-law-combats-silent-menace-electric-cars. (Accessed 13 October 2019).
[42] R. Stone, in: 4th ed.Introduction to Internal Combustion Engines, Red Globe Press, Basingstoke, 2012, 2012.
[43] Breaking! Tesla increases supercharging V2 speeds as S & X get on-route battery warmup | CleanTechnica. https://cleantechnica.com/2019/04/26/breaking-tesla-increases-supercharging-v2-speeds-as-s-x-get-on-route-battery-warmup/ (Accessed 13 October 2019).
[44] Terms and Exclusions: Kia 7 Year warranty | kia motors UK, kia motors. https://www.kia.com/uk/innovation/7-year-warranty/terms-and-exclusions/ (Accessed 13 October 2019).
[45] M. Fries, M. Kerler, S. Rohr, S. Schickram, M. Sinning. An Overview of Costs for Vehicle Components, Fuels, Greenhouse Gas Emissions and Total Cost of Ownership Update 2017, University of California, Davis, Institute of Transportation Studies, 2017.
[46] EQUA Index - independent real-world driving data. https://equaindex.com/ (Accessed 13 October 2019).
[47] New diesel cars cleaner than prescribed. https://presse.adac.de/meldungen/adac-ev/technik/neue-diesel-pkw-sauberer-als-vorgeschrieben.html (accessed October 13, 2019).
[48] O. US EPA, Highlights of the Automotive Trends Report, US EPA, 2016. https://www.epa.gov/automotive-trends/highlights-automotive-trends-report. (Accessed 13 October 2019).
[49] R.D. Reitz, H. Ogawa, R. Payri, T. Fansler, S. Kokjohn, Y. Moriyoshi, A. Agarwal, D. Arcoumanis, D. Assanis, C. Bae, K. Boulouchos, M. Canakci, S. Curran, I. Denbratt, M. Gavaises, M. Guenthner, C. Hasse, Z. Huang, T. Ishiyama, B. Johansson, T. Johnson, G. Kalghatgi, M. Koike, S. Kong, A. Leipertz, P. Miles, R. Novella, A. Onorati, M. Richter, S. Shuai, D. Siebers, W. Su, M. Trujillo, N. Uchida, B.M. Vaglieco, R. Wagner, H. Zhao, IJER editorial: the future of the internal combustion engine, Int. J. Engine Res. (2019), https://doi.org/10.1177/1468087419877990, 1468087419877990.
[50] G. Kalghatgi, Is it really the end of internal combustion engines and petroleum in transport? Appl. Energy 225 (2018) 965–974, https://doi.org/10.1016/j.apenergy.2018.05.076.
[51] K. Hyatt, The average age of cars on America's roads went up again, report says, Roadshow. https://www.cnet.com/roadshow/news/average-vehicle-age-increase-america/ (Accessed 13 October 2019).
[52] Average vehicle age | ACEA - european automobile manufacturers' association. https://www.acea.be/statistics/tag/category/average-vehicle-age (Accessed 13 October 2019).
[53] A. Baskin, Africa used vehicle report. https://wedocs.unep.org/bitstream/handle/20.500.11822/25233/AfricaUsedVehicleReport.pdf?sequence=1&isAllowed=y, 2018.
[54] N. Powell, N. Hill, J. Bates, N. Bottrell, M. Biedka, B. White, T. Pine, S. Carter, J. Patterson, S. Yucel, Impact Analysis of Mass EV Adoption and Low Carbon Intensity Fuels Scenarios – Summary Report, Ricardo, 2018. https://www.concawe.eu/wp-content/uploads/RD18-001912-3-Q015713-Summary-Report-Mass-EV-and-Low-Carbon-Fuels-Scenarios-1-1.pdf.
[55] B. Biermann, J. Behrenroth, T. Burchell, Ways towards Low CO2 and Low Emissions Powertrains. https://futurepowertrains.co.uk/wp-content/uploads/2017/12/Bernhard-Biermann.pdf, 2018.
[56] T. Mendiara, F. García-Labiano, A. Abad, P. Gayán, L.F. de Diego, M.T. Izquierdo, J. Adánez, Negative CO2 emissions through the use of biofuels in chemical looping technology: a review, Appl. Energy 232 (2018) 657–684, https://doi.org/10.1016/j.apenergy.2018.09.201.
[57] W. Leitner, J. Klankermayer, S. Pischinger, H. Pitsch, K. Kohse-Höinghaus, Synthese, motorische verbrennung, emissionen: chemische aspekte des

kraftstoffdesigns, Angew. Chem. 129 (2017) 5500–5544, https://doi.org/10.1002/ange.201607257.

[58] T. Searchinger, R. Heimlich, R.A. Houghton, F. Dong, A. Elobeid, J. Fabiosa, S. Tokgoz, D. Hayes, T.-H. Yu, Use of U.S. Croplands for biofuels increases greenhouse gases through emissions from land-use change, Science 319 (2008) 1238–1240, https://doi.org/10.1126/science.1151861.

[59] E.S. Shuba, D. Kifle, Microalgae to biofuels: 'Promising' alternative and renewable energy, review, Renew. Sustain. Energy Rev. 81 (2018) 743–755, https://doi.org/10.1016/j.rser.2017.08.042.

[60] Pathway certified carbon intensities. https://ww3.arb.ca.gov/fuels/lcfs/fuelpathways/pathwaytable.htm (Accessed 13 October 2019).

[61] D. Gschwend, P. Soltic, A. Wokaun, F. Vogel, Review and performance evaluation of fifty alternative liquid fuels for spark-ignition engines, Energy Fuels 33 (2019) 2186–2196, https://doi.org/10.1021/acs.energyfuels.8b02910.

[62] T. Larsson, O. Stenlaas, A. Erlandsson, Future Fuels for DISI Engines: A Review on Oxygenated, Liquid Biofuels, SAE International, Warrendale, PA, 2019, https://doi.org/10.4271/2019-01-0036.

[63] Co-optimization of fuels & engines, energy.gov. https://www.energy.gov/eere/bioenergy/co-optimization-fuels-engines (Accessed 13 October 2019).

[64] C.S. Sluder, Estimation of the fuel efficiency potential of six gasoline blendstocks identified by the U.S. Department of energy's Co-optimization of fuels and engines program, SAE Int. J. Adv. & Curr. Prac. in Mobility. 1 (2019) 189–200, https://doi.org/10.4271/2019-01-0017.

[65] E. Kasseris, J.B. Heywood, S. Seitz, R. Kolakaluri, Real world performance of an onboard gasoline/ethanol separation system to enable knock suppression using an octane-on-demand fuel system, 2018-01–0879, https://doi.org/10.4271/2018-01-0879, 2018.

[66] Y. Putrasari, O. Lim, A review of gasoline compression ignition: a promising technology potentially fueled with mixtures of gasoline and biodiesel to meet future engine efficiency and emission targets, Energ. 12 (2019) 238, https://doi.org/10.3390/en12020238.

[67] Directive 2003/30/EC of the European Parliament and of the Council on the promotion of the use of biofuels or other renewable fuels for transport, Off. J. Eur. Union (2003), 0042:0046:EN:PDF, https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2003:123.

[68] Modifications to Fuel Regulations to Provide Flexibility for E15; Modifications to RFS RIN Market Regulations, Federal Register, 2019. https://www.federalregister.gov/documents/2019/03/21/2019-05030/modifications-to-fuel-regulations-to-provide-flexibility-for-e15-modifications-to-rfs-rin-market. (Accessed 13 October 2019).

[69] P.O. of the E. Union, Impact of higher levels of bio components in transport fuels in the context of the Directive 98/70/EC of the European Parliament and of the Council of 13 October 1998, relating to the quality of petrol and diesel fuels and amending Council Directive 93/12/EEC: final report.. https://publications.europa.eu/en/publication-detail/-/publication/ec1f67bd-5499-11e7-a5ca-01aa75ed71a1, 2017. (Accessed 13 October 2019).

[70] J. Artz, T.E. Müller, K. Thenert, J. Kleinekorte, R. Meys, A. Sternberg, A. Bardow, W. Leitner, Sustainable conversion of carbon dioxide: an integrated review of catalysis and life cycle assessment, Chem. Rev. 118 (2018) 434–504, https://doi.org/10.1021/acs.chemrev.7b00435.

[71] L.E. Hombach, L. Doré, K. Heidgen, H. Maas, T.J. Wallington, G. Walther, Economic and environmental assessment of current (2015) and future (2030) use of E-fuels in light-duty vehicles in Germany, J. Clean. Prod. 207 (2019) 153–162, https://doi.org/10.1016/j.jclepro.2018.09.261.

[72] F.E.V. Marketing, Almost CO2-neutral Mobility, FEV Corporate Magazine, 2018. http://magazine.fev.com/en/almost-co2-neutral-mobility/. (Accessed 13 October 2019).

[73] S. Verhelst, J.W. Turner, L. Sileghem, J. Vancoillie, Methanol as a fuel for internal combustion engines, Prog. Energy Combust. Sci. 70 (2019) 43–88, https://doi.org/10.1016/j.pecs.2018.10.001.

[74] James WG. Turner, Andrew GJ. Lewis, Sam Akehurst, Chris J. Brace, Sebastian Verhelst, Jeroen Vancoillie, Louis Sileghem, Felix Leach, Peter P. Edwards, Alcohol fuels for spark-ignition engines: performance, efficiency and emission effects at mid to high blend rates for binary mixtures and pure components, n.d. https://journals.sagepub.com/doi/full/10.1177/0954407017752832, 2018. (Accessed 13 October 2019).

[75] K. Zhao, Methanol fuel blending in China. https://www.methanol.org/wp-content/uploads/2019/02/6.-Kai-Zhao-Methanol-Fuel-Blending-in-China.pdf, 2019.

[76] China backs methanol-powered cars as part of cleaner energy drive - caixin global. https://www.caixinglobal.com/2019-03-21/china-backs-methanol-powered-cars-as-part-of-cleaner-energy-drive-101395250.html (Accessed 13 October 2019).

[77] E. Bannon, E-fuels Too Inefficient and Expensive for Cars and Trucks, but May Be Part of Aviation's Climate Solution – Study | Transport & Environment, Transport & Environment. (2017). https://www.transportenvironment.org/press/e-fuels-too-inefficient-and-expensive-cars-and-trucks-may-be-part-aviations-climate-solution-%E2%80%93 (Accessed 13 October 2019).

[78] D. Stanton, High efficient clean combustion for SuperTruck. https://www.energy.gov/sites/prod/files/2014/03/f8/deer10_stanton.pdf, 2010.

[79] U. Åstrand, The Wärtsilä 31 - the world's most efficient 4-stroke engine, J. Japan Inst. Mar. Eng. 51 (2) (2016).

[80] Energy department announces 37 million investment in commercial and passenger vehicle efficiency, Energy.Gov. https://www.energy.gov/articles/energy-department-announces-137-million-investment-commercial-and-passenger-vehicle (Accessed 13 October 2019).

[81] R. Morgan, A. Atkins, G. Dong, M.R. Heikal, C. lenartowicz, The recuperated split cycle - experimental combustion data from a single cylinder test rig, SAE Int. J. Engines 10 (2017), https://doi.org/10.4271/2017-24-0169.

[82] J. Finneran, C.P. Garner, M. Bassett, J. Hall, A review of split-cycle engines, Int. J. Engine Res. (2018), https://doi.org/10.1177/1468087418789528, 1468087418789528.

[83] N. Papaioannou, F.C. Leach, M.H. Davy, A. Weall, B. Cooper, Evaluation of exhaust gas recirculation techniques on a high-speed direct injection diesel engine using first law analysis, Proc. Inst. Mech. Eng. - Part D J. Automob. Eng. 233 (2019) 710–726, https://doi.org/10.1177/0954407017749110.

[84] B. Johnson, C. Edwards, Exploring the pathway to high efficiency IC engines through exergy analysis of heat transfer reduction, SAE Int. J. Engines 6 (2013) 150–166, https://doi.org/10.4271/2013-01-0278.

[85] Y. Wakisaka, M. Inayoshi, K. Fukui, H. Kosaka, Y. Hotta, A. Kawaguchi, N. Takada, Reduction of heat loss and improvement of thermal efficiency by application of "temperature swing" insulation to direct-injection diesel engines, SAE Int. J. Engines 9 (2016) 1449–1459, https://doi.org/10.4271/2016-01-0661.

[86] P. Lu, C. Brace, B. Hu, C. Copeland, Analysis and comparison of the performance of an inverted Brayton cycle and turbocompounding with decoupled turbine and continuous variable transmission driven compressor for small automotive engines, J. Eng. Gas Turbines Power 139 (2017), https://doi.org/10.1115/1.4035600.

[87] S.L. Miller, M.N. Svrcek, K.-Y. Teh, C.F. Edwards, Assessing the feasibility of increasing engine efficiency through extreme compression, Int. J. Engine Res. 12 (2011) 293–307, https://doi.org/10.1177/1468087411404299.

[88] J.R. Fyffe, M.A. Donohue, M.C. Regalbuto, C.F. Edwards, Mixed combustion–electrochemical energy conversion for high-efficiency, transportation-scale engines, Int. J. Engine Res. 18 (2017) 701–716, https://doi.org/10.1177/1468087416665936.

[89] Electricity Statistics, IEA. https://www.iea.org/statistics/electricity/, 2019. (Accessed 13 October 2019).

[90] V.R.J.H. Timmers, P.A.J. Achten, Non-exhaust PM emissions from electric vehicles, Atmos. Environ. 134 (2016) 10–17, https://doi.org/10.1016/j.atmosenv.2016.03.017.

[91] H. Hao, Z. Mu, S. Jiang, Z. Liu, F. Zhao, GHG emissions from the production of lithium-ion batteries for electric vehicles in China, Sustainability 9 (2017) 504, https://doi.org/10.3390/su9040504.

[92] T.R. Hawkins, B. Singh, G. Majeau-Bettez, A.H. Strømman, Comparative environmental life cycle assessment of conventional and electric vehicles, J. Ind. Ecol. 17 (2013) 53–64, https://doi.org/10.1111/j.1530-9290.2012.00532.x.

[93] R. Vidhi, P. Shrivastava, A review of electric vehicle lifecycle emissions and policy recommendations to increase EV penetration in India, Energ. 11 (2018) 483, https://doi.org/10.3390/en11030483.

[94] J.W. Brennan, T.E. Barder, Battery Electric Vehicles vs. Internal Combustion Engine Vehicles, Arthur D. Little, 2016.

[95] R. Kawamoto, H. Mochizuki, Y. Moriguchi, T. Nakano, M. Motohashi, Y. Sakai, A. Inaba, Estimation of CO2 emissions of internal combustion engine vehicle and battery electric vehicle using LCA, Sustainability 11 (2019) 2690, https://doi.org/10.3390/su11092690.

[96] D. Wu, F. Guo, F.R. Field, R.D. De Kleine, H.C. Kim, T.J. Wallington, R.E. Kirchain, Regional heterogeneity in the emissions benefits of electrified and lightweighted light-duty vehicles, Environ. Sci. Technol. 53 (2019) 10560–10570, https://doi.org/10.1021/acs.est.9b00648.

[97] S.J. Jones, If electric cars are the answer, what was the question? Br. Med. Bull. 129 (2019) 13–23, https://doi.org/10.1093/bmb/ldy044.

[98] Simply amazing new nissan LEAF | 100% electric car | NISSAN. https://www.nissan.co.uk/vehicles/new-vehicles/leaf.html (Accessed 13 October 2019).

[99] Global lithium-ion battery planned capacity grows 4% in a single month — charts! | CleanTechnica. https://cleantechnica.com/2019/03/31/global-lithium-ion-battery-planned-capacity-grows-4-in-a-single-month-charts/ (Accessed 13 October 2019).

[100] Estimated worldwide automobile production from 2000 to 2018, Statista. https://www.statista.com/statistics/262747/worldwide-automobile-production-since-2000/ (Accessed 13 October 2019).

[101] Hybrids Are 14 Times Better than Battery Electric Vehicles at Reducing Real-World Carbon Dioxide Emissions, Emissions Analytics. https://www.emissionsanalytics.com/news/hybrids-are-better (Accessed 13 October 2019).

[102] All-New Ford Escape Brings Style and Substance to Small SUVs with Class-Leading Hybrids, Flexibility and Exclusive Technology | Ford Media Center. https://media.ford.com/content/fordmedia/fna/us/en/news/2019/04/02/all-new-ford-escape-brings-style-substance-small-SUVs.html (Accessed 13 October 2019).

[103] A. Joshi, Benefits of electric and hybrid vehicles depends on upstream CO2 emissions, LinkedIn, 2019. LinkedIn, https://www.linkedin.com/pulse/benefits-electric-hybrid-vehicles-depends-upstream-co2-ameya-joshi/. (Accessed 13 October 2019).

[104] A. Elgowainy, J. Han, J. Ward, F. Joseck, D. Gohlke, A. Lindauer, T. Ramsden, M. Biddy, M. Alexander, S. Barnhart, I. Sutherland, L. Verduzco, T.J. Wallington, Current and future United States light-duty vehicle pathways: cradle-to-grave lifecycle greenhouse gas emissions and economic assessment, Environ. Sci. Technol. 52 (2018) 2392–2399, https://doi.org/10.1021/acs.est.7b06006.

[105] TMC, New analysis of plug-in hybrid car MPG and emissions is expected to spark debate on their suitability for fleet operation, the miles consultancy. https://www.themileconsultancy.com/, 2017. (Accessed 13 October 2019).
[106] The smart fortwo micro hybrid drive (mhd): even more economical and environmentally friendly thanks to start/stop function, MarsMediaSite. https://media.daimler.com/marsMediaSite/en/instance/ko/The-smart-fortwo-micro-hybrid-drive-mhd-Even-more-economical-and-environmentally-friendly-thanks-to-startstop-function.xhtml?oid=9919399 (Accessed 13 October 2019).
[107] Electrified vehicles claim more than 50 per cent of Toyota motor Europe new car sales during first half of 2019 - Toyota UK media site. https://media.toyota.co.uk/2019/07/electrified-vehicles-claim-more-than-50-per-cent-of-toyota-motor-europe-new-car-sales-during-first-half-of-2019/ (Accessed 13 October 2019).