

Chapter 18

The Industrial Ecology of the Automobile

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Abstract For the last 100 years, virtually every automobile was an internal combustion vehicle (ICV) powered by either gasoline or diesel and mostly made from steel. Even as the ICV was identified as a source of serious environmental impact, it continued to outcompete others, arguably more environmentally benign, transportation modes. Banning lead from gasoline, requiring catalytic converters, and increasing powertrain efficiency allowed the ICV to respond to environmental criticism and continue its dominance over other transportation technologies. Today, well over one billion ICVs are in use worldwide.

Since the turn of the last century, however, this dominance is beginning to be contested, not so much from other transportation modes but from alternative automotive designs and fuels, such as biofuels, lightweight materials, and fuel cell, hybrid, and battery electric powertrains. All of these alternatives are meant to decrease the environmental impacts of cars, but in all cases there is concern about trade-offs, unintended consequences, and regrettable substitutions. This chapter discusses history and recent developments of automobiles from an industrial ecology perspective. Such a perspective is necessary to determine the extent to which the emerging automotive technologies can genuinely reduce rather than simply shift the environmental impacts of automobiles.

Keywords Industrial ecology of automobiles • Environmental sustainability of cars • Biofuels • Advanced powertrains • Lightweight automotive materials

1 Introduction

Since time immemorial people and goods had been transported by horse-drawn carriages. This changed in the late nineteenth century, when self-propelled carriages started to appear in Europe and the United States. In 1897 the New York Times predicted that “the mechanical wagon with the awful name automobile [...] has

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come to stay.” The newspaper went on to say that “man loves the horse, and he is not likely ever to love the automobile” (Cohn 2009). We all know which one of those two predictions was wrong.

After a century of undisputed domination, the gasoline- or diesel-powered internal combustion vehicle (ICV) finally has to contend with some serious competition. The staple automotive material, steel, has also come under considerable competitive pressure. Interestingly, all contenders, be they biofuels, hydrogen, hybrid or pure electric powertrains, aluminum, or fiber-reinforced polymers, are all marketed as ways to reduce the environmental impacts of cars. For this reason, the demand for industrial ecology expertise, especially life cycle assessment, has increased significantly in the automotive world. While all these developments are relatively recent, the history of environmental concerns caused by cars is almost as old as the history of the car itself.

The modern automobile, or car, was first created in Europe in the late nineteenth century by inventors and entrepreneurs such as Karl Benz, Gottlieb Daimler, and Wilhelm Maybach. It is based on four-stroke gasoline or diesel engines, invented, among others, by Nikolaus Otto and Rudolf Diesel, even though cars using steam engines and electric motors were also developed at that time. While electric vehicles (EVs) enjoyed considerable success in the early twentieth century, continuous improvement of ICV design and performance together with a steady decline in ICV prices and increasing availability of gasoline lead to an eventual demise of the EV industry by 1920. After the turn of the century, supply and demand of ICVs started to increase rapidly, both in Europe and in the United States. While France was initially the largest producer of vehicles, it was soon overtaken by the United States, which introduced and perfected mass production of vehicles. No car epitomizes the affordable, mass-produced automobile more than the Model T, introduced by Henry Ford in 1908. Over 15 million models were produced worldwide by the time Ford ceased production of the Model T in 1927.

The first environmental drama began to unfold in 1921 when Thomas Midgley, who was working for Charles Kettering at the General Motors Research Corporation, discovered tetraethyl lead's (TEL) excellent antiknock properties and patented it (Kitman 2000). Both were aware of viable antiknock alternatives to TEL which couldn't be patented, such as ethanol. The toxicity of lead had been known for several thousand years, and the proposal to use TEL as gasoline additive almost instantly sparked public health controversies. Acute lead poisoning was common in the early TEL production plants. In fall 1924, 5 of 49 TEL workers in Standard Oil's Bayway Refinery in New Jersey died of acute lead poisoning, and 32 had to be hospitalized. As a result, New York City, New Jersey, and Philadelphia banned leaded gasoline, jeopardizing GM, DuPont, and Standard Oil's plan to make TEL the leading antiknock additive. To address and preempt growing public health concerns about TEL, General Motors commissioned research from the US Bureau of Mines in 1923 and asked the Surgeon General Hugh Cumming to hold public hearings in 1925. The hearings were inconclusive and charged an expert committee to further investigate the public safety of TEL. While some experts mentioned the risk of chronic exposure, all official reports and statements focused on the risk of acute lead

poisoning and eventually declared TEL's use as gasoline additive safe. The existence of less toxic alternatives, such as ethanol, was ignored by both the industry and relevant public health officials.

By the early 1960s, TEL was in virtually all US gasoline and was quickly expanding in the rest of the world. Around the same time cars were identified as a major source of photochemical smog in highly motorized areas such as Los Angeles. That ICVs powered by (leaded) gasoline cause significant environmental problems finally became undeniable when scientists started to notice dangerous and rising levels of lead in the environment and human blood, and the smog caused by cars went from bad to worse. In the early 1970s, US car makers decided to use catalytic converters to meet the emerging tailpipe emission standards. This was bad news for TEL, which poisons catalytic converters. At the same time the recently founded US EPA started to consider phasing out leaded gasoline to reduce chronic lead exposure. TEL was eventually banned in California in 1992 and in the rest of the United States in 1996. In the EU, catalytic converters became mandatory in 1990, and lead was finally banned in 2000.

By then, the use of lead in gasoline had caused catastrophic levels of lead pollution. While lead levels in human blood decrease quickly in regions where leaded gasoline is banned, TEL is still used in many developing economies, and elevated levels of lead can be found in virtually every corner of the earth. Banning TEL required the use of an alternative antiknock. The United States and other countries decided to use methyl tertiary butyl ether (MTBE) to replace lead, a typical material substitution approach to pollution prevention. Unfortunately, MTBE is highly water soluble, and even small fuel spills can contaminate large amounts of groundwater. MTBE may also be a carcinogen. This is an example of the environmental trade-offs that are frequently involved in substitution approaches. As a result, the use of MTBE has been phased out in the United States, which now uses ethanol as antiknock and oxygenate, the same substance that was ignored in the 1920s. There seems to be a certain amount of reinventing the wheel in environmental problem solving. The rediscovery of reusable bags, containers, and packaging come to mind here.

Three-way catalytic converters are classic end-of-pipe technology designed to control pollution. They are extremely successful in reducing CO, NO_x, and hydrocarbon emissions from vehicles but require platinum and slightly reduce powertrain performance. More importantly, it could be argued that they have enabled staggering levels of ICV ownership and use. This means that photochemical smog is still a major problem in areas like Los Angeles, only now caused by vast numbers of low or ultralow-emission vehicles as opposed to the fewer cars with high emissions in the 1960s. Also, catalytic converters do nothing to CO₂, so the enormous proliferation of ICVs, partially enabled by this end-of-pipe technology, leads to an equal increase in automotive greenhouse gas (GHG) emissions, which has finally come under scrutiny. In 2006, the UNFCCC reported rising GHG emission trends and noted that "in particular, transport remains a sector where emission reductions are urgently required but seem to be especially difficult to achieve."

Initially, environmental automotive regulation focused on the air pollutants CO, VOC, NO_x, and PM. After the oil crisis in 1973, the United States also added fuel

economy standards. Today, over 70 % of the global new vehicle market is subject to GHG and/or fuel economy standards (Miller and Façanha 2014). This worldwide commitment to automotive emission reductions has led car manufacturers to rethink the automobile. The prevalent car design, the steel-based ICV powered by gasoline or diesel, is being challenged by alternative fuels, powertrains, and structural materials. The following sections will discuss these developments from an industrial ecology perspective. Such a perspective is necessary to determine whether these alternatives offer overall environmental impact reductions or instead shift burdens to other life cycle stages or other environmental concerns.

2 Biofuels

Biofuels are not an invention of the modern environmental movement but were commonplace until coal began to fuel the industrial revolution in the second half of the eighteenth century. The diesel engine at the World Fair in Paris in 1900 ran on peanut oil, and Rudolf Diesel himself believed that vegetable oil would become an important fuel. An early version of Otto's engine ran on ethanol. The Model T was designed to run on gasoline or ethanol, and Henry Ford thought that ethanol was the fuel of the future. In the 1930s gasoline blended with ethanol from corn was proposed in the United States to support its ailing agriculture. High oil prices and oil shortages during World War II and the oil crises in the 1970s briefly renewed US interest in corn ethanol. These phases were short-lived, however, and gasoline and diesel from petroleum became and remained the exclusive fuels for the growing fleet of ICVs in the United States.

The same is true for the rest of the world, with the exception of Brazil, where ethanol from sugarcane has been used to fuel cars since the 1920s. Brazilian ethanol production increased steadily until cheap oil became consistently available after World War II. However, prompted by the oil crises in the 1970s, Brazil launched a National Ethanol Program in 1975 (Garten Rothkopf 2007). Among other things, this program included ethanol subsidies and mandated that all gasoline be blended with ethanol at certain ratios and that ethanol be sold at lower prices than gasoline. As a result, Brazil became the world's largest fuel ethanol producer and consumer by far. In the 1980s oil prices tumbled to historic lows, where they stayed until the end of the millennium. This eroded the economic case for ethanol, and Brazilian production was relatively flat during that period at around 11–15 billion liters per year (EIA 2015).

Between 1981 and 2001, annual corn ethanol production in the United States increased at a slow but steady pace from 0.3 to 6.7 billion liters, which was mainly fostered by subsidies. After 2000, progressive replacement of MTBE with ethanol further helped to increase US production. However, the big boost for US ethanol came with the creation of the Renewable Fuel Standard (RFS) program in the Energy Policy Act of 2005 and its expansion in the Energy Independence and Security Act of 2007. In 2007, the United States produced 18.5 billion liters of

ethanol and overtook Brazil as the world's largest producer. The surge in corn ethanol production in the United States was accompanied by an increasingly heated debate about its energy and GHG benefits. A growing number of so-called fuel cycle or well-to-wheel studies became available with a wide range of contradictory findings. Fuel cycle or well-to-wheel analyses are essentially life cycle assessments (LCAs) of fuels, even though many of the early studies were from researchers outside of the LCA community and without reference to existing LCA standards.

Studies by Patzek and Pimentel received particular media attention as they found that, over its life cycle, corn ethanol requires more fossil energy inputs than it has calorific value and emits more GHGs than gasoline. Studies from other research groups, however, concluded that cumulative fossil energy demand and life cycle GHG emissions of corn ethanol are substantially lower than those of gasoline. A meta-analysis intent on settling the controversy was probably one of the first LCAs published in the journal *Science*, even though it never mentions the term LCA (Farrell et al. 2006). Unsurprisingly, the study found that the wide range in results was due to differences in inventory data, system boundaries, and coproduct allocation. It concluded that the GHG savings of corn ethanol are moderate but those of cellulosic ethanol substantial. Unfortunately, producing cellulosic ethanol, also called second-generation biofuel, is much more difficult than starch- and sugar-based ethanol, since it is very hard to break down the lignocellulosic feedstock in an economically viable way. So hard, in fact that the US Environmental Protection Agency (EPA) retroactively reduced the 2013 RFS target volume for cellulosic ethanol from 1 billion gallons to 810,185 gallons (EPA 2014a).

The environmental reputation of biofuels received its next challenge in 2008, when two studies in the same issue of *Science* reported their findings on the GHG implications of land use change (LUC) (Fargione et al. 2008; Searchinger et al. 2008). Fargione et al. found that clearing land for fuel crop production creates a significant "carbon debt" and that biofuels require 17 to 420 years to generate GHG savings of the same size. Searchinger et al. argued that using feedstock from existing fields does not avoid this issue since it induces indirect land use change (iLUC) by removing the crop from its prior market. For example, corn used for ethanol is now missing as animal feed, which causes land conversion for new corn production elsewhere. Searchinger et al. conclude that corn and cellulosic ethanol have higher GHG emissions than gasoline when iLUC is included. Naturally, these strong findings were contested by many, including biofuel associations and the US Department of Energy. California's Low Carbon Fuel Standard (LCFS) and the new RFS include GHG emissions from iLUC but with conflicting results. The controversy about LUC and iLUC continues. Both effects are prime examples of consequential LCA and thus question the usefulness of attributional LCA for environmental decision making (Plevin et al. 2014). It is interesting to note that none of the original LUC and iLUC researchers came from the industrial ecology or LCA communities.

The next twist in the biofuel saga came the following year with two more *Science* publications. The first pointed out that turning fuel crops into electricity for battery electric vehicles (BEVs) rather than biofuels for ICVs would roughly double crop-to-wheel conversion efficiency (Ohlrogge et al. 2009). The second showed how this

translates into substantially larger life cycle energy and GHG benefits, even if you consider that BEVs have significantly larger cradle-to-gate production energy inputs and GHG emissions than equivalent ICVs (Campbell et al. 2009). However, one major drawback of any sun-to-wheels transportation pathway based on biomass is that the energy conversion efficiency of photosynthesis is typically below 1 % (Blankenship et al. 2011). This means that vast areas of land are needed to harvest significant amounts of solar energy (McDonald et al. 2009). A much more efficient alternative would be direct photovoltaic conversion into electricity. Such a PV-BEV system is orders of magnitude more land use efficient than even the most optimistic biomass scenarios and has equal or higher energy and GHG benefits (Geyer et al. 2013). PV-powered BEVs are conceptually appealing but have some technical and operational challenges, one of which is the timing of PV power supply and EV charging demand.

3 Powertrains

Electric vehicles had all but vanished by 1920, apart from some niche applications such as the iconic British milk float. The modern era of the EV began when General Motors (GM) unveiled a BEV prototype called Impact at the 1990 Los Angeles Auto Show. This was encouraging news for the California Air Resources Board (CARB), which had been working on a low-emission vehicle (LEV) program to help areas such as Los Angeles meet federal air quality standards (Collantes and Sperling 2008). CARB had come to the conclusion that improvements in conventional powertrains alone would not achieve the required emission reductions. As a result, CARB added a so-called zero-emission vehicle (ZEV) mandate to the LEV program of 1990. The mandate specifies that car sales of the major manufacturers had to be composed of at least 2 % ZEVs by 1998, 5 % by 2001, and 10 % by 2003. A ZEV is defined as having no tailpipe emissions of air criteria pollutants. CARB clearly had BEVs in mind, but since its regulation has to be technology neutral, it pointed out that fuel cell vehicles (FCVs) would also meet the definition. The ZEV mandate is arguably the single biggest driver behind the emergence of alternative powertrains. It is interesting to note that it emerged from concerns over air quality and not oil resources or climate change. In the United States, fuel economy can only be regulated at the federal level. After a White House proposal to increase fuel economy standards failed in congress in 1992, the Clinton administration started the Partnership for a New Generation of Vehicles (PNGV) with the goal to develop dramatically more fuel-efficient powertrains (Malakoff 1999). The research collaborative, which was cancelled in 2001 by the Bush administration, focused on diesel-electric hybrids and FCVs rather than BEVs.

In late 1997 Toyota's Prius, the first mass-produced hybrid-electric vehicle (HEV), went on sale in Japan. A few years later, Honda and Toyota started selling HEVs in the United States. In contrast, only a number of concept vehicles were created under the PNGV program. Measured in ZEV sales, California's ZEV mandate

was also not a success. Between 1996 and 2003 just over 4,400 BEVs, such as GM's EV1 and Toyota's electric RAV4, were leased or sold (Bedsworth and Taylor 2007). The ZEV mandate had to be amended many times to make it achievable. First, the 1998 and 2001 ZEV sales requirements were dropped. Next, new vehicle categories and alternative compliance pathways were created. It became possible to substitute BEV sales with larger sales of HEVs and smaller sales of FCVs. If this sounds all very complicated that's because it is. Thanks to the LEV program and its ZEV mandate, California has now a veritable zoo of vehicle categories. Ten years after GM introduced the Impact, BEVs were all but forgotten again. HEV sales climbed steadily, though, and more and more car manufacturers offered hybrid-electric versions of their models. At the same time FCVs were increasingly seen as the automotive endgame, with car companies and governments making bold announcements about the impending rollout of hydrogen cars and infrastructure. While mass-produced FCVs always appeared to be another 5 years away, BEVs returned with a roar in the form of the Tesla Roadster in 2008. Since then many BEV and plug-in hybrid-electric (PHEV) models have entered the market, the most successful of which are the Nissan Leaf, the Chevy Volt, and the plug-in Prius. And just when people started to wonder whether hydrogen cars were a pipe dream after all, Toyota revealed the Mirai at the 2014 Los Angeles Auto Show, the first commercially available FCV.

All four challengers of the incumbent ICV involve an electric motor and a traction battery. This allows all of them to recover and store the car's kinetic energy through regenerative braking. However, motors and batteries differ in size and the way they are used. In parallel HEVs, the electric motor is combined with an internal combustion engine (ICE), and both provide torque to the wheels. With typical values between 1 and 2 KWh, HEVs have the smallest traction batteries and thus the smallest all-electric driving range. HEVs still use liquid fuels, typically gasoline or diesel, as their exclusive energy source. In PHEVs the traction battery can be charged directly from an external electric power source. With typical values between 5 and 10 KWh, it is larger than in HEVs, which increases all-electric driving range. BEVs and FCVs use only electric motors for traction and typically don't contain any internal combustion engines. An interesting exception is the Chevy Volt which has a gasoline engine but uses it only to charge the battery. FCVs have batteries for intermediate energy storage but use hydrogen tanks for main energy storage. The fuel cell converts the hydrogen into electricity. Hydrogen is an energy carrier, not an energy source, and needs to be produced first. Earlier plans for on-board hydrogen production, e.g., through hydrocarbon reforming, are no longer being pursued. In BEVs the only energy storage device is the battery, and the only traction device is the motor. BEVs therefore have the simplest powertrains but also require the largest batteries.

Battery technology, in particular cost and energy density, has improved substantially over the years and is a key determinant in alternative powertrain choice and design. GM's EV1 used lead-acid batteries. Toyota's HEVs use nickel metal hydride (NiMH) batteries with roughly double the energy density. All BEVs use lithium ion (Li-ion) chemistries with roughly four times the energy density of lead-acid

batteries. It is thus the energy density of Li-ion batteries that enabled the latest reemergence of the BEV, even though they still have smaller driving ranges and longer charging times than ICVs. It has also been pointed out that EVs are only as clean as the electricity they use, a somewhat obvious observation for industrial ecologists (Moyer 2010).

Relative to the incumbent ICV, alternative/advanced powertrains have higher tank-to-wheel energy efficiency but also higher cradle-to-gate production impacts, due to the nature of their components, such as batteries, fuel cells, and electric motors (Demirdöven and Deutch 2004; ANL 2014). In the case of HEVs, it is relatively simple to show that the fuel savings far outweigh the additional production impacts. Life cycle comparisons of the other alternative powertrains are complicated by the fact that they use electricity and hydrogen as fuel, which can be produced in many different ways (Samaras and Meisterling 2008; Notter et al. 2010; Hawkins et al. 2012). Currently, most hydrogen is produced through steam reforming of hydrocarbon fuels. To eliminate the need for fossil fuels, it is frequently stated that the hydrogen for FCVs should ideally come from electrolysis of water powered by renewable electricity. However, it would be considerably more energy efficient to use renewable electricity directly in BEVs rather than convert it into hydrogen through electrolysis and then back into electricity in a fuel cell. The detour via hydrogen has the advantage, though, that hydrogen is easier to store than electricity.

4 Lightweight Materials

In addition to more efficient powertrains, the PNGV also researched lightweight materials for vehicle mass reduction. Such a mass reduction increases the fuel economy of the vehicle without reducing its size. The use of lightweight materials is usually also seen as necessary to compensate for the higher mass of advanced powertrains. A material is regarded as lightweight if it achieves significant mass reduction relative to mild steel without compromising other design parameters, but there is no precise definition. The considered materials are typically aluminum and magnesium alloys, fiber-reinforced polymers, and advanced high-strength steels (AHSS) (DOE 2014). With the exception of AHSS, the primary production of lightweight materials has significantly higher environmental impacts than mild steel production. In fact mass reduction potential appears to be correlated to production impacts (Geyer 2013). Again, LCA is required to quantify the trade-off between the increase in material production emissions and the decrease in vehicle use phase emissions. The trade-off needs to be studied on a case-by-case basis, but different studies of similar cases frequently yield conflicting results. There is significant debate about the amount of mass reduction lightweight materials can achieve in practice, since this is not directly observable and has to be either modeled or derived from analysis of proxy data sets. The same is true of the relationship between vehicle mass reduction and fuel economy improvement. Initial use of simplistic rules of thumb is

slowly being replaced by physics-based powertrain models (Koffler and Rohde-Brandenburger 2010). It turns out, for example, that the regenerative braking and the higher efficiency of advanced powertrains significantly reduce the impact of vehicle mass reduction on fuel economy. This challenges the gospel that advanced powertrains require lightweight materials. Other sources of uncertainty are the assumed total mileage of the vehicle and, as always, the inventory data of the involved processes, such as material and fuel production.

By far the most contentious issue, however, is the question of how recycled content and end-of-life recycling impacts the net environmental benefits of lightweight automotive materials (Geyer 2008). The controversy over how to account for material recycling is generic to LCA and not specific to vehicle mass reduction. There is a plethora of literature explaining, comparing, and reviewing the various existing recycling methodologies. In the case of lightweight automotive materials, changing recycling methodology can change the rank-ordering of the results, which is highly unsatisfactory. Consequential system expansion is the only way to determine the actual effects of material recycling. Environmental studies of lightweight materials, just like those of biofuels, therefore call into question the usefulness of attributional LCA for public policy making. Attempts at consequential LCA, on the other hand, highlight the large uncertainties intrinsic to consequential analysis. Car manufacturers all know and use LCA and are well aware of its ambiguities in particular with regard to recycling. Policy makers are currently reluctant to change automotive emission regulations from tailpipe to life cycle, regardless of the fact that the latter perspective is superior in principle.

As a result, all public policy on automotive GHG emissions focuses on fuel economy or tailpipe CO₂ (Miller and Façanha 2014). None use a full life cycle perspective; in particular vehicle production impacts are ignored by all of them. Many car manufacturers therefore see lightweight materials as an important way to meet these standards. So far, Ford made the boldest move and decided to make the body structure of the 2015 model of its most successful vehicle, the F150 pickup truck, entirely aluminum. Ford states that this enabled mass reductions of up to 700 pounds (318 kg) and fuel economy improvements of up to 20 % relative to 2014 model. While it is clear that such a dramatic change to America's best-selling vehicle is an enormous economic gamble, it is unclear what the net climate change impacts of this move are. Rather than trying to predict the consequences of such a change, say through consequential LCA, we are now running the experiment. Luckily, this experiment is bound to have a less dramatic outcome than the one of adding lead to gasoline.

5 Conclusions

The use of automobiles experienced phenomenal growth ever since cars started being mass-produced just over 100 years ago. Today, well over one billion vehicles are in use worldwide (OICA 2015). In 2013 alone, over 65 million cars and almost

22 million commercial vehicles were added. Thanks to rapidly developing economies like China and India, there is no end of this growth in sight.

Serious efforts to reduce the environmental impacts of this ever-growing vehicle fleet are relatively recent. In the EU, catalytic converters became mandatory only 25 years ago, and lead was banned only 15 years ago. The United States moved earlier to reduce air pollutants from cars but is lagging in terms of fuel efficiency. In fact, the fuel economy of new light-duty vehicles in the United States declined between 1987 and 2004 (EPA 2014b). This trend was driven by increases in vehicle weight, power, and acceleration and also the growing share of so-called sports utility vehicles (SUVs), wiping out all advances in engine and powertrain efficiency. These trends are currently flat or at least increasing more slowly.

It is unlikely, though, that this is enough to reduce the environmental impacts from a huge and growing global car fleet to acceptable levels, which is why more and more decision makers are looking for a new automotive paradigm. It is currently unclear what will be the future fuel, powertrain, or even material of the car. It is clear, however, that the tools and concepts of industrial ecology could and should play a vital role in evaluating environmental trade-offs and avoiding unintended consequences. Humans have a substantial track record of causing large environmental problems, the conventional ICV being one of them. Yet humans are also starting to build a track record of solving environmental problems. Let's hope that with the enlightened use of industrial ecology, the future automobile will be one such solution.

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