Research Report – UCD-ITS-RR-19-45

Internal Combustion Engine Bans and Global Oil Use

November 2019

Lewis M. Fulton
Co-Director, Sustainable Transportation Energy Pathways Program, Institute of Transportation Studies, University of California, Davis, lmfulton@ucdavis.edu

Amy Myers Jaffe
Corresponding author, David M. Rubenstein Senior Fellow, Council on Foreign Relations, New York, ajaffe@cfr.org

Zane McDonald
Formerly Graduate Researcher, Institute of Transportation Studies, University of California Davis, zlmcdonald@ucdavis.edu

An Institute of Transportation Studies Program

Abstract

Automotive transport represents one of the highest contributing sources of oil use, local air pollution, and greenhouse gas emissions. Several countries, notably including several European countries and China, have proposed bans on the sale of automotive internal combustion engine (ICE) vehicles as a means to abate these negative effects from the sector. Some cities and regions have already instituted restrictions on ICE vehicles. Larger, national bans have been discussed as a policy to begin in 2040. We consider the literature on proposed policies to ban ICE vehicles and develop scenarios to estimate the potential impacts of these proposed bans, to contribute to a peaking in oil demand and eventual reductions in CO_2 emissions. We find that national level ICE car bans in key markets such as China and Europe in 2040 could reduce oil use by five million barrels a day (b/d) by 2050, under five percent of projected global oil use. A global ban would eliminate three times that level of oil use but would likely take several decades for its full impact is realized. Our findings suggest that other supporting policies beyond the bans alone might be necessary to trigger more rapid changes in markets and purchase behavior.

Key Points:

- **Proposed ICE LDV sales bans could cut oil use by about 5 million barrels per day by 2050; a global ICE LDV sales ban could cut oil use by over 15 million barrels a day over a 20 year period.**
- **National ICE sales bans will have delayed impacts because of the decadal nature of LDV stock turnover rates;-thus, the bans are sensitive to implementation date.**
- **Sales bans will likely need supporting policies implemented many years beforehand to create strong incentives and a glide path to reach specified targets.**

Contents

Abbreviations

2DS, two degree scenario
4DS, 4 Degree Scenario
ASEAN, Association of South East Asian Nations
b/d, barrels per day
CO2, carbon dioxide
CO2e, carbon-dioxide-equivalent GHG emissions
EJ, exajoules
EPA, Environmental Protection Agency
EU, European Union
f, fuels
GDP, gross domestic product
GHG, greenhouse gas
ICE, internal combustion engine
iCET, Innovation Center for Energy and Transportation
IEA, International Energy Agency
Km^2, square kilometers
LDV, light-duty vehicle
m, modes
Mboe/d, million barrels of oil equivalent per day
MoMo, Mobility Model
Mmbd, million barrels per day
Mtonnes CO_2eq, million tons of carbon dioxide equivalent
NDC, Nationally Determined Contributions
NO2, nitrogen dioxide
OECD, Organization for Economic Co-operation and Development
OEM, original equipment manufacturer
PEV, plug-in electric (and plug-in hybrid electric) vehicle
Pkm/y, passenger kilometer miles per year
PLDV, passenger light duty vehicles
ROW, rest of world
RTS, reference technology scenario
SAV, shared autonomous vehicle
Vkt, vehicle kilometers traveled
WTW, well to wheel

1. Introduction

Several countries around the globe have announced plans to ban sales of automotive internal combustion engine (ICE) vehicles after 2040 as a key policy to reduce air pollution and greenhouse gas emissions. Patrick Plotz et al suggest in a recent survey on designing ICE car bans that ICE vehicles need to be banned completely by 2035 or 2040 to "align with deep GHG-reduction goals." Plotz et al (2019) note that since new passenger vehicles tend to be used for fifteen years or longer (oftentimes across multiple owners and countries), ICE car bans need to be implemented suitably early and convincingly to ensure companies develop sufficient alternative fuel vehicle model lines, supply chains, and manufacturing expertise. The International Energy Agency (IEA), Ford Motor Company, and others have published glide paths that show that sales of ICE cars must fall to close to zero by 2050 to remain consistent with a 2 degrees C warming scenario (IEA 2017, Ford Motor Company 2019, Kodjak 2019). For automotive original equipment manufacturers (OEMs), this implies expansion of adequate manufacturing capacity and key supply chains to meet the rapidly rising demand for plug-in electric and plug-in hybrid electric vehicles (PEVs), (we refer to PEVs broadly to include also fuel cell vehicles that do not require charging by plug-in), theorized in a glide path to zero ICE sales. For governments, this implies supporting the transition away from incumbent ICE cars to PEVs through education, electric recharging infrastructure expansion, supply and demand side sales incentives, and fuel price regulation including fuel taxes and environmental performance standards.

In practice, details regarding how such bans would be implemented remain vague. A recent study on how to implement a national ban in China suggests a phased approach could be necessary. Innovation Center for Energy and Transportation (iCET), a leading Chinese and U.S. think tank focused on Chinese environmental policy sponsored China Oil Consumption Cap Plan and Policy Research Project, which has an advisory role to government policy makers in China, recently unveiled a discussion paper on China's timetable and possible methodology to phase out traditional ICE engine vehicles (iCET, 2019). China's automotive policies are highly influential because China represents the largest car market in the world, with total sales of over 23.6 million light duty cars in 2018. Automobiles accounted for over forty percent of China's total oil consumption in 2018. To-date, China's Dual Credit policy, concurrent with PEV sales quotas and relaxed consumer PEV purchase regulations have brought China's PEV industry into a leading position globally. Going further, China's Hainan province has officially announced it will ban ICE vehicles by 2030. China is investing heavily in new energy vehicles, including PEVs, which have been receiving subsidies and other support to meet China's energy saving, air quality, and decarbonization goals. The Chinese study suggests Beijing will want to implement the ban in stages, starting in major cities and eventually reaching across the country. Vehicles used for ride sharing and municipal fleets would be regulated first, followed by private passenger cars, iCET suggests.

Other regions are taking a different approach. For example, British Columbia has instituted an electric vehicle mandate as an interim step to its new law to end new sales of ICE engines by 2040. Oslo, Norway is the first city to implement an ICE ban in its center city. Other cities including London, Barcelona, Copenhagen, Seattle, and Hainan, China, have citywide bans planned for 2030. National level bans, if fully implemented and successful, would supersede city level policies. Expectations that over 80 percent of the global population may live in cities by 2050 (Rose, 2016) leaves room for city level bans in countries that do not have a national ban to have significant impact as well. Many other cities are investigating how to cut both the numbers and impacts of vehicles to reduce air pollution and congestion. (O'Shaughnessy, et al, 2016)

As shown in Figure 1, many countries including France, the U.K., India, and China, have made announcements regarding future restrictions on new sales of ICE cars by 2040 or sooner. Reduction or outright bans of ICE cars in city centers are also catching on in many locations (Garfield, 2018). A number of major cities have pledged to restrict diesel and gasoline ICE vehicles between 2024 and 2040 (IEA, 2018). Even U.S. legislators have proposed bills banning on gasoline ICE engine vehicles, though passage is not yet considered politically viable (Hawkins, 2019)

Figure 1. Intended Bans on Internal Combustion Engines

Source: Burch, I. and Gilchrist, J. 2018. "Survey of Global Activity to Phase Out Internal Combustion Engine Vehicles," Center for Climate Protection, https://climateprotection.org/wp-content/uploads/2018/10/Survey-on-Global-Activities-to-Phase-Out-ICE-Vehicles-FINAL-Oct-3-2018.pdf

The question on what would replace ICE passenger vehicles is a contentious one. Some policy analysts argue that cities will need to strengthen public transit and increase the capacity for bike lanes and walking, if a ban on ICE engine cars is going to be possible (Fulton, 2017). Others expect large numbers of PEVs to be purchased to offset the elimination of ICE vehicles at both the city and national level. These could include much larger numbers of ride-hailing fleet vehicles and/or automated vehicles, as long as they were not ICE vehicles. Cumulative sales of PEVs reached 5 million in 2018. However, only a few regions, such as Norway, Beijing and parts of California, have significant electric vehicles sales as part of the emerging car stocks.

A decline in the use of ICE vehicles, both for passenger cars and possibly commercial trucks, will have an impact on global oil use, which may peak at some point in the next two decades. Shifts away from oil use in light duty vehicles (LDVs) would likely speed this process. The existing literature on peak oil demand focuses mainly on the role of energy efficiency and fuel switching in lowering demand for oil products (conventional oil production and unconventional oil production) by 2070 (Brandt et al, 2013). Brown and Huntington 2017 note the importance of reducing world oil demand as a means to enhance world oil security. Newman, Beatley, and Boyer 2009 argue that for cities to be resilient to climate change and other health challenges, they will need to reduce oil demand.

To date, there are no large (>500,000 inhabitants) cities completely free of passenger light duty vehicles (PLDVs) (Nieuwenhuijsen and Khreis, 2016). Venice and the Medina of Fez in Morocco are among the best examples, but PLDV use in these cities is limited organically by practical constraints (Wright, 2005). Within the last few years, there has been growing interest among some cities in setting increasingly ambitious goals to restrict PLDVs from entering high-use areas such as city centers (often referred to as car-free zones or pedestrian zones). Hamburg was the first city to announce that it will be free of private car use by 2034 (Reuters, 2015). Norway's capital, Oslo, quickly followed with a goal to become "car-free" by 2019. In reality, this policy restricts cars from only 1.9 km^2 of Oslo's downtown, in addition to an existing car-free waterfront promenade and central station. Similarly, Madrid has limited the number of visiting vehicles in its downtown and plans to completely pedestrianize its urban center (3.52km^2) by 2020, though recent developments have called the viability of this program into question (Cathkart-Keays, 2015). In Europe alone, there are 32 cities considering implementation of a car-free zone (Tønnesen, 2016).

Car-free zones are "proto-type" car free cities and in many cases, cities may simply extend these restrictions over time to cover more area. Cities may also specify to allow zero-emission vehicles into these zones (including bicycles, electric vehicles, and in some cases plug-in hybrid vehicles), thus making them potentially equivalent to ICE car bans.

In some cases, cities may eventually consider shifting to automated autonomous electric vehicles in geo-fenced areas. Some cities, like Las Vegas, Nevada, and Austin, Texas, are already experimenting with autonomous public buses. Pilots are also underway utilizing automated flying drone taxis that would travel from one rooftop to another, bypassing the street. The distinction between banning all cars and banning only ICE cars is of course very important in terms of its potential impacts. Banning all cars is likely to have a major impact on mode choice; banning only ICE vehicles may have a mixed impact, affecting both mode choice and fuel choice. Notably, in an ICE ban situation, battery electric and fuel cell vehicles would likely be permitted; plug-in hybrid vehicles may also be, especially if they can function in zero-emissions mode while in the affected zone as was studied by Ford Motor Company in London (Ford Motor Company, 2017). We include all these vehicle types in our use of the term PEV.

National level car bans would obviously be the most definitive approach to altering future car stocks and could have by far the biggest impacts on sales of ICE vs non-ICE vehicle technologies (Spitzer, 2018). As is already happening with diesel bans in Europe, a top down approach might suggest car manufacturers would anticipate the coming restrictions and start to adjust their manufacturing and sales strategies accordingly. Car owners too would not likely want to buy cars of a technology that is being phased out for fear of rapid depreciation and possible dwindlingof access to repair services, spare parts, and fueling stations. Though not addressed directly by this report, it is worthy of note that many economies rely heavily on domestic and international auto manufacturing. Thus, it may be less politically palatable for some governments to enact regulation that quickly changes ICE manufacturing jobs and endangers traditional auto parts supply chain businesses. We believe this is a pivotal reason why national ban announcements to date have been vague and aspirational in nature, except in countries that do not have significant domestic car industries.

In this paper, we investigate how effective ICE car bans could be in eliminating oil use. We compare scenarios of partial phase-ins of bans to a globalized ban in various time frames and how this translates into reductions in oil use and related carbon dioxide emissions. Finally, we examine whether bans alone are likely to result in a smooth glide path or whether other, complementary policies will have to be adopted alongside changes in passenger vehicle technology. We discuss those policies and subjects for future research.

2. Methodology and Data

For the analysis of the effects of ICE bans in this study, on a national and global level, we have developed scenarios and projections using a global vehicle sales and stock model, calibrated to align with the modeling framework used by the International Energy

Agency (IEA) in its widely-cited, complex Mobility Model (MoMo). Unlike MoMo, our tool is a relatively simplified stock adjustment model, including all light-duty vehicle sales and stock for 8 world countries and regions (adding up to global totals). Our modeling tool is informed by the methodology of the more complex and detailed MoMo model, which is described in Fulton et al, 2009. Our sales and stock model tracks new vehicle and average car stock technology types, energy efficiency, and typical travel levels. Our approach is aimed to provide enough detail to understand how changes in future sales of LDVs by vehicle technology type will affect the stock and energy use by kind of energy (e.g. gasoline, diesel, electricity, hydrogen, etc.). Scenario calculations are, in turn, linked to vehicle efficiency, energy use, and CO2 emissions. These calculations and projections are based on the "ASIF" methodology, which relates vehicle Activity, Stock, energy Intensity and Fuel carbon intensity (Schipper et al, 1999). More formally, this multiplicative relationship can be characterized as:

$$G = \sum_{m,f} A_{m,f} S_{m,f} I_{m,f} F_{m,f}$$

> where *A* is the travel activity (e.g. kms) per vehicle, *S* is the vehicle stock, *I* is the energy use per km of driving for the average vehicle, and *F* is the CO2 emissions per unit fuel use. These are assessed across all modes (*m*) or vehicle types and all fuel types (*f*). The sum product of this equation is G, the total greenhouse gas emissions from all vehicles. (In this study only light-duty vehicles are considered, so other modes are excluded.)

Using this framework, we were able to create scenarios where sales of ICE vehicles of different types are targeted for phase out by specific dates, with a glide path over a 10 or 15-year period to zero. Changes in these sales are then tracked through to stock changes, travel changes, and energy/CO2 impacts. We create a "business-as-usual" baseline scenario that builds off and aligns with assumptions and inputs from IEA's published ETP (2017) Reference Technology Scenario (RTS), also called their 4 Degree Scenario (4DS) (IEA, 2017). Like the IEA ETP, this baseline projection of car stocks and car travel takes into account policy changes, either enacted or expected to be enacted, within the near term. We refer to this reference case as the "Baseline". We then consider and construct separate cases with much faster overall penetration of electric vehicles and other changes in efficiency, but within the same overall vehicle ownership projection in each country.

In utilizing our stocks modeling tool, we started from Baseline projections of vehicle sales by vehicle type and region and utilized the sales and stock-turnover functions to adjust future sales by vehicle type and derive changes to the stock, energy use, and GHG emissions. In other words, new scenarios were constructed by altering our reference case baseline, by changing specific assumptions regarding the sales (and energy technologies) of new vehicles at certain points in the future. We did not alter total sales, total stock, or travel per vehicle, though at a future date, scenarios that consider how autonomous technology or urban zoning might change these elements are a good subject for further research.

It should be noted that there is considerable fuel efficiency improvement (though modest adoption of zero-emission vehicles) in the baseline scenario. ICCT (2019), among others, have found that substantial improvements in ICE passenger vehicle efficiency are still possible, with current emissions rates as high as 250 grams of CO2 per kilometer dropping to as low as 60 to 70 grams per kilometer (g/km) by 2030, which is now a formal EU target for LDVs (EU Commission, 2030). The ICCT study shows that such levels could be achieved just with non-ICE vehicle penetration. An earlier ICCT study (Meszler et al, 2016) indicates that passenger vehicle standards as low as 40 g/km can be achieved by 2030 for costs between 1,300 and 3,000 Euros per vehicle at 2014 currency values. Our baseline does not achieve such low GHG levels for ICE but does incorporate significant improvements and reductions, along with considerable increases in vehicle stocks and travel around the world.

2.1 National ICE vehicle sales ban scenarios

In our modeling tool, we define the parameters of an internal combustion engine (ICE) sales ban policy as one where non-plugin, ICE-powered vehicle sales go to zero in participating countries by 2040. Plug-in hybrids are assumed to be exempt from the sales ban, as well as commercial freight vehicles, emergency vehicles, and 2/3 wheelers. However, stricter bans are possible, which would presumably yield more reductions than we consider with these bounding conditions in this paper.

In our analysis, we assume the policy begins to impact sales in 2030 as automobile manufacturers (OEMs) begin to gradually shift production. This assumption is informed by car manufacturers' response to substantive bans on diesel engines in several European cities. A number of OEMs have pledged to cease production of all diesel powertrains within the next decade (IEA, 2018). One driving factor is a rapid consumer response. German sales of diesel vehicles fell by 20 percent in 2017 and continue to decline, and sales value of used diesel vehicles have plummeted. (Hockenos, 2018) U.K. diesel vehicles sales have fallen even more precipitously (Campbell, 2018). This is consistent with research findings that policies that discourage diesel sales and/or promote electric vehicles can be effective in encouraging rapid shifts from diesel engine to electric vehicle technology. (Brand, 2016)

Additionally, the idea of an anticipatory response to the policy is consistent with recent actions made by auto manufacturers after national commitments to phasing out ICEs became public. In fact, there is considerable action occurring today, and a major transition to PEV sales appears likely to be well underway by 2030. For example, Volvo recently announced it will exclusively produce cars with some form of electric motor (hybrids, plug-in hybrids and/or full battery electric vehicles) beginning in 2019 (Pham). Larger producers such as General Motors, BMW, Renault-Nissan and most others have begun to roll out many more electric models and plan to ramp this up in coming years. As of early 2019, Daimler is planning for 10 plug-in models by 2022, BMW is planning for 25 models by 2025, VW is aiming for 30 or more EVs and annual vehicle sales of 2 to 3 million vehicles by 2025, and General Motors plans to offer at least 20 new fully electric models by 2023 (Marklines, Davies). These shifts are monumental due to the scale of these companies, but are not surprising given the trends unfolding in California, Europe, and China, all sizable, important automotive markets. In particular, China has aggressively pursued policies to increase the share of electric vehicles in the national PLDV stock. In 2018, more than one million light-duty EVs were sold in China (Green Car Congress, 2019), with EVs making up 2.2 percent of total PLDV stock (IEA, 2019).

An important question, therefore, is whether these announcements indicate that bans already are having effect, and a steady glide path is assured toward zero ICE sales by 2040. This is a difficult question but it is important to consider that there are literally thousands of ICE models sold around the world today, and even if manufacturers are producing dozens or even hundreds of plug-in models by 2030, this may not represent a steady glide path to zero ICE cars. National ICE car bans focused on a 2040 target date are not likely to have a significant impact on sales before 2030 because consumers do not appear to look that far ahead in their decision-making, and many automakers plan changes in platforms and tooling in six to eight year increments. On the other hand, there could be a some type of psychological effect of knowing of a future ban on markets before 2030, and particularly if there are policies in place to support moving onto a substitution glide path (such as purchase incentives), then impacts before 2030 are possible. We assume a slow, steady increase in PEV sales up to 2030 due to a combination of these effects, but then a much faster ramp up to 2040 as bans are well established and are “looming”, i.e. fall within planning horizons.

Another key factor is the geographic range of bans – we assume they are first implemented in major car producing regions that have already announced intentions and are clearly moving in that direction, namely OECD Europe and China. India has announced bans (for 2030) but has not taken any clear steps to signal that these policy pronouncements are serious or will be enforced or supported with other policies, so we do not include India in this first group.

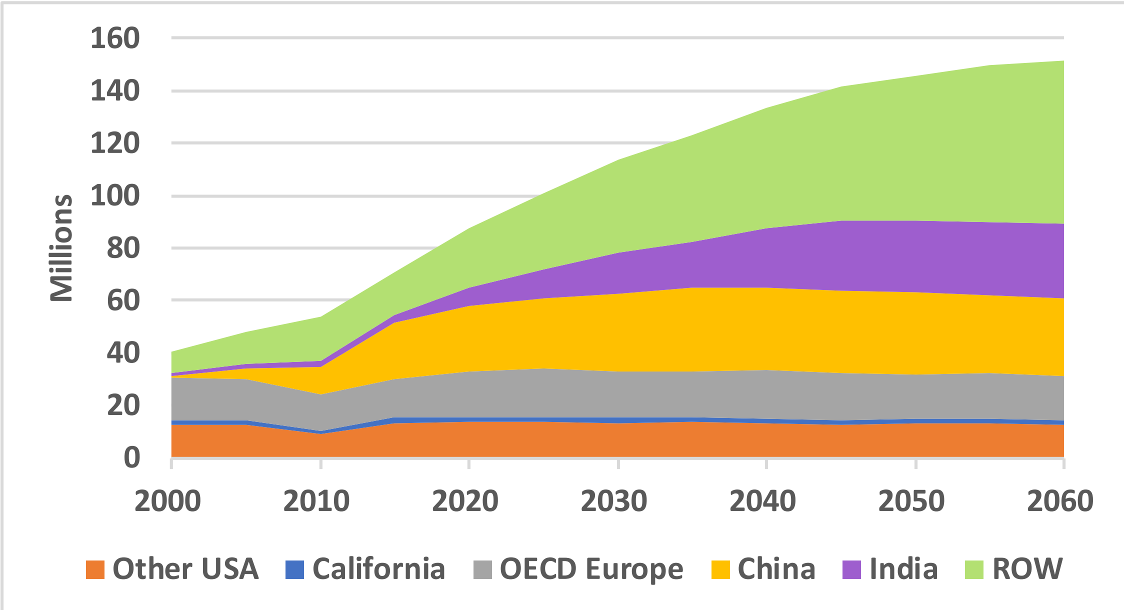
We then consider a second group that includes India and other countries that are either considering bans or seem likely to do so if bans in the first group remain in play in the coming years. This second wave group includes India, the United States, Canada, Japan, South Korea, Australia and New Zealand – basically adding all of the other OECD countries outside of Europe and India. Added to the first group, this represents the vast majority of light-duty vehicle production and sales today – though the share will decline over time as the rest of the world increases their sales rates and shares of global sales.

In our last scenario, we assume that the rest of the world follows suit, but with a five-year lag time. This group includes countries like Russia, Brazil, South Africa, and all the remaining countries of the world, in Asia, nearly all of Africa, and Latin America. Thus, in this broader scenario, no ICE vehicles are sold anywhere in the world after 2045.

Throughout all these scenarios, we assume a preservation of the "base case" projection of car sales and stock worldwide. We use the IEA 4 Degrees sales projections which are forecast to grow from the current levels of around 95 million per year to nearly 150 million by 2050 (Figure 2). After 2030, much of projected vehicle sales growth occurs outside of OECD regions or China. Based on this growth in non-OECD regions, global vehicle stocks are projected to grow from their current level of just over 1 billion to well over 2 billion by 2050. It is possible that rising congestion in mega-cities in the non-OECD will curb this projected growth. We consider this potential outcome as good subject for future research.

Our analysis substitutes PEVs into this sales/stock projection; i.e., wherever ICE vehicles are banned and thus no longer sold, we assume that a vehicle purchase is still made but substituted by an electric vehicle or hydrogen fuel cell. This has a direct, complete impact on oil use (as long as electricity generation uses no oil) but does not necessarily cut CO2 emissions completely, since electricity generation triggers some emissions.

Figure 2. Global Light-duty Vehicle Sales by Region



It is of course quite possible that individual car ownership trends might change over time, and deviate significantly from our business as usual assumptions used here. For example, a shift to PEVs could be accompanied by lower driving levels and a transformation of urban travel away from private automobiles, toward on-demand and shared mobility options. Automation may further move urban populations away from individual vehicle ownership to a higher reliance on "on demand" services that might become much less expensive (Jaffe, 2019). These effects would likely reduce overall car sales and stocks over time. They could render our projections about car stocks and energy use too high, and change the time frame and glide path toward an ICE ban future. However, there are simply too many possible future scenarios to consider to be able to address them in this initial paper. We begin this first effort by sticking to a more traditional baseline future, to compare the effects of car bans as the only feature of change.

In summary, we assume that the actions being taken by governments, in terms of policies, and manufacturers and in terms of product planning today are beginning to reflect some "back of mind" thinking on possible future ICE bans, but not yet sufficiently to put companies on a glide path toward those bans. There will need to be many other policies in play to push markets in the right directions, at least through 2030. This paper does not attempt to detail those, or conduct a policy modeling analysis of a wider range of sensitivity analysis. We are focused on what the glide path from 2030 to 2040 might look like under a straightforward ICE ban implementation and how this would affect the stock of vehicles through 2040 and beyond, and thus oil use. Specifically, we assume

LDV bans begin significantly to influence sales in all affected regions by 2030, with a ramp up to full market transformation by 2040. In this regard, we make a number of other specific assumptions:

- LDV ICE bans are implemented completely by 2040 in covered countries, with the exception that in our global ban case, the countries added to that case achieve a ban in 2045.
- The ban restricts non-plug-in vehicles, so there are some ICEs still, in the form of plug-in hybrids.
- Stock turnover continues normally, meaning the last operating ICE vehicles are not phased out until 15-20 years after the ban date.
- We consider a business-as-usual case with no bans, and 3 ban scenarios:
    - Bans only in those countries that currently seem most likely – namely the EU countries and China.
    - Bans extended to include India (which has made ban announcements) and the rest of the OECD (US/Japan/Korea/Canada/Australia/New Zealand) in addition to the EU and China.
    - Bans further extended to become globally by 2045, to capture the larger effect were the entire world to go along with the ban effort with a five-year lag time given the high percentage of car manufacturers already located in ban regions.
- Consumers and manufacturers see this date approaching and start to shift away from ICE cars much sooner, beginning in earnest in 2030. The period 2030-2039 is handled as a transition period with a steady decline in ICE vehicle market shares in covered regions.
- We take into account that other policies are already affecting PEV sales worldwide and we ramp up sales from today to 2030 following that path, which is a much slower rate than once the ban-related trends kick in in 2030.
- LDV mobility and vehicle ownership are fully conserved; overall new vehicle sales, stocks, and kilometers of travel (Vkt) remain consistent across all scenarios.

As mentioned, there are many reasons why the future may take a different course than we depict here. For example, LDV sales reach 160 million by 2050, which may not occur if the world moves to a “shared mobility” ride-hailing framework with far fewer vehicles used far more intensively, providing 12 or more hours of daily commercial service. We are also aware of the possibility ever-rising car sales and stocks could result in traffic congestion so severe that the system is unsustainable from that point of view, which could result in massive shifts away from car use. There could also be very different population and/or GDP evolution, resulting in different car ownership from those drivers.

2.2 Baseline Scenario

To create a baseline scenario, we align with projections from the IEA ETP 2017 New Policies Scenario, which in turn is consistent with IEA's "4 Degree Scenario" work from its World Energy Outlook forecasting. Under this baseline scenario, car sales and stock growth are robust into the future, and there are some electric vehicle sales into the future in this scenario. Worldwide, sales rise from about 95 million in 2018 to 160 million by 2050, with stocks rising from 1.1 billion to 2.3 billion over this time. PEV sales rise from around 3 million in 2020 to 33 million in 2050 (or 20% market share), and stocks from 10 million to 280 million, or about 12% of LDV stocks. Along with strong increases in average new LDV fuel economy over this period, the net result is relatively small increase in transport oil use – from around 22 million barrels/day in 2020 to 24 million in 2050. This actually begins to decline after a 2045 peak of 25 million b/d, so there is an LDV oil peak even in the baseline, but it is better termed "flat oil" since it does not decline much after this point, but rather remains steady.

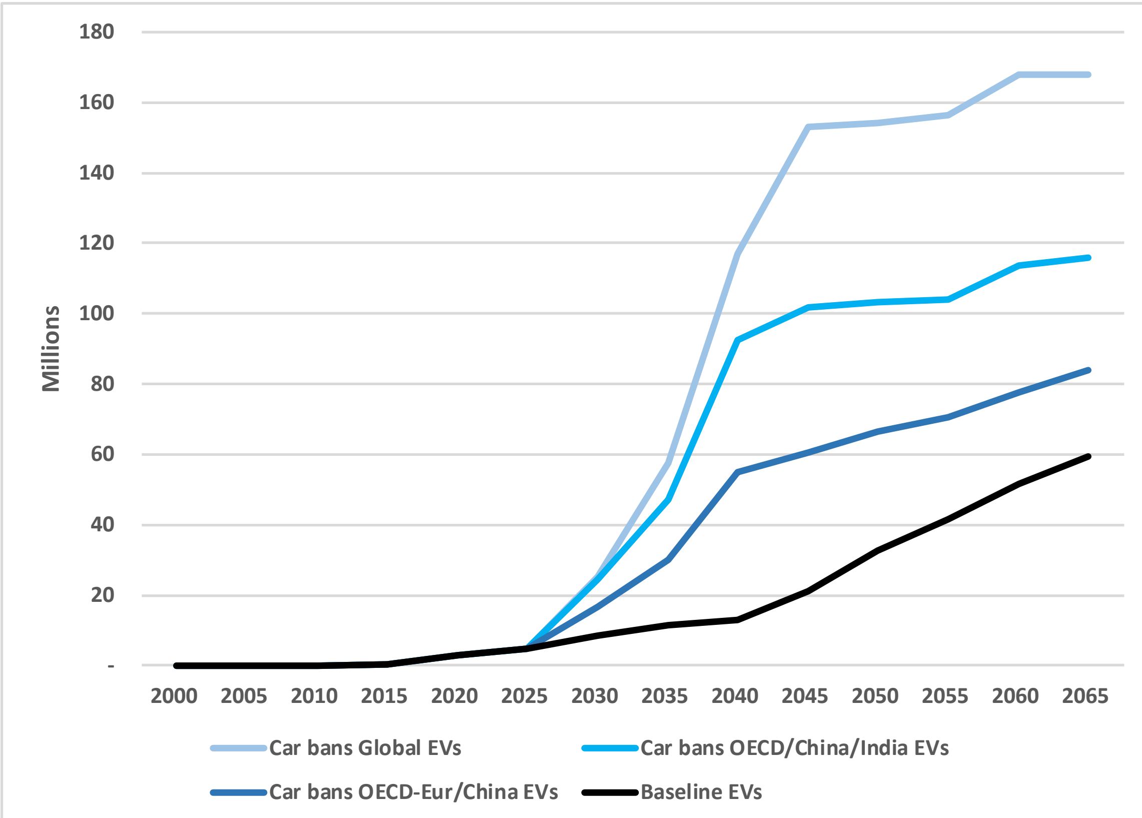
2.3 Carbon Emissions Calculation Methodology

We also use our modeling tool to estimate well-to-wheel GHG (as CO2-equivalent) emissions from LDVs in this analysis. This is a straightforward calculation, with a CO2 coefficient for gasoline, diesel, and electricity in each year, in each country/region, all contained within the model. We use the International Energy Agency's projections for electricity CO2 intensity under their 2 degrees scenario. IEA calculates that CO2 emissions per kWh of electricity generation are projected to decline in all countries in the 2DS scenario (IEA, 2018). We use the 2DS scenario for our base projections in all scenarios, but also consider the differences from using RTS carbon intensity projections. Our operating assumption is that decarbonization in the utility sector is generally taking place at a more rapid pace than in the transportation sector and thus a political atmosphere that would encourage ICE bans would likely also have consistent carbon reduction policies in the utility sector.

3. Results

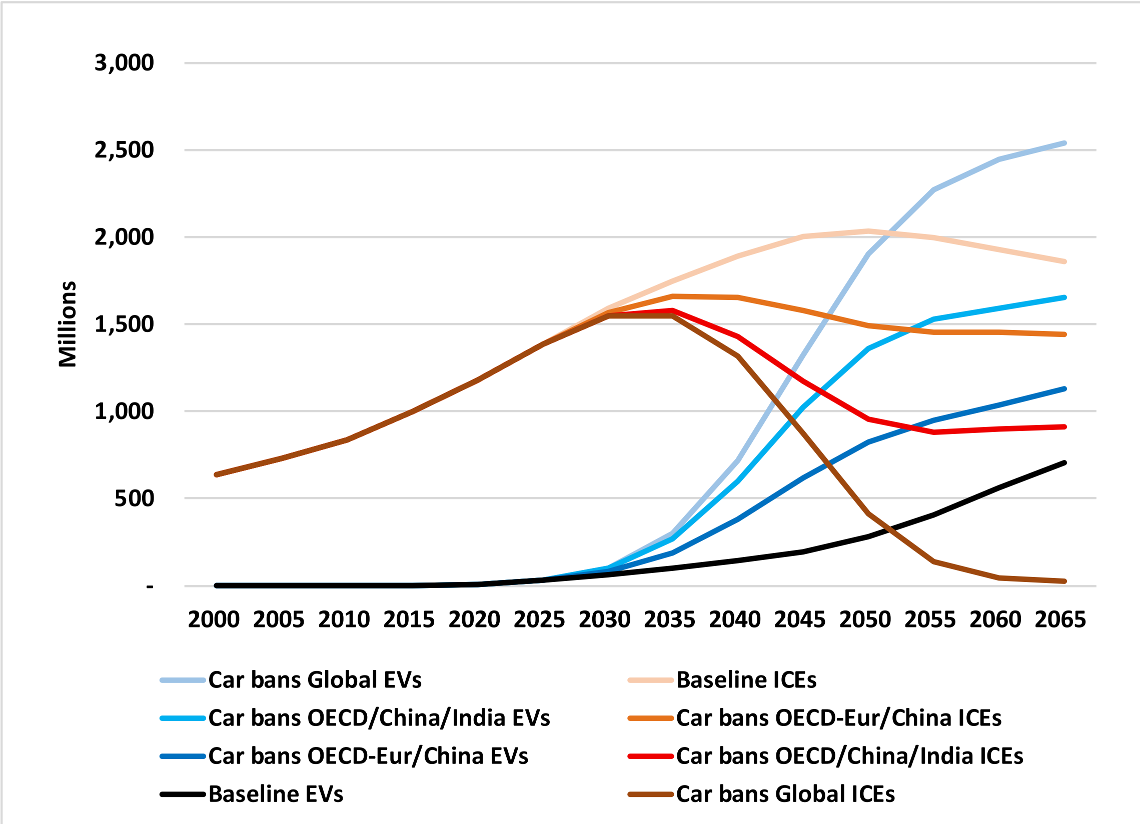
The results from our three different ICE engine ban scenarios on global vehicle sales by engine type is shown in Figure 3. Changes in sales of PEVs between 2020 and 2065 are a function of the regional car bans in place for each scenario. With fully effective bans by 2040 in OECD Europe and China, about 60 million PEVs are sold, displacing a similar number of ICE vehicles. With the rest of the OECD (US/Canada/Japan/Korea/Australia/New Zealand) and India added, the number rises to nearly 100 million. If the entire rest-of-world followed, with a five year time lag (so that all ICEs are banned worldwide by 2045), there would be sales of nearly 160 million PEVs in that year. In each scenario, after the ban year, the share of PEVs remains stable and grows just as a function of overall LDV sales.

Figure 3. Global Plug-in Electric Vehicle Sales, Four Scenarios



Significantly, the rate of change promoted by national ICE sales bans slows by the rate of vehicle stock turnover (Figure 4). By 2040, bans in OECD-Europe and China result in about a 20% PEV stock share of all LDVs (400 million out of 2 billion). Even with bans worldwide, plug-in stocks only approach one third of the total stock. This share then increases rapidly over time: in the global scenario, by 2050 PEVs reach 85% of the global LDV stock (about 2 billion out of 2.3 billion LDVs). By 2060 the transition is about complete. The slow rate of turnover of the existing car fleet dampens the effectiveness of ICE ban policies to affect oil use and carbon emissions within the 2050 time frame.

Figure 4. Global PLDV Stock Shares Resulting from Sales Projections

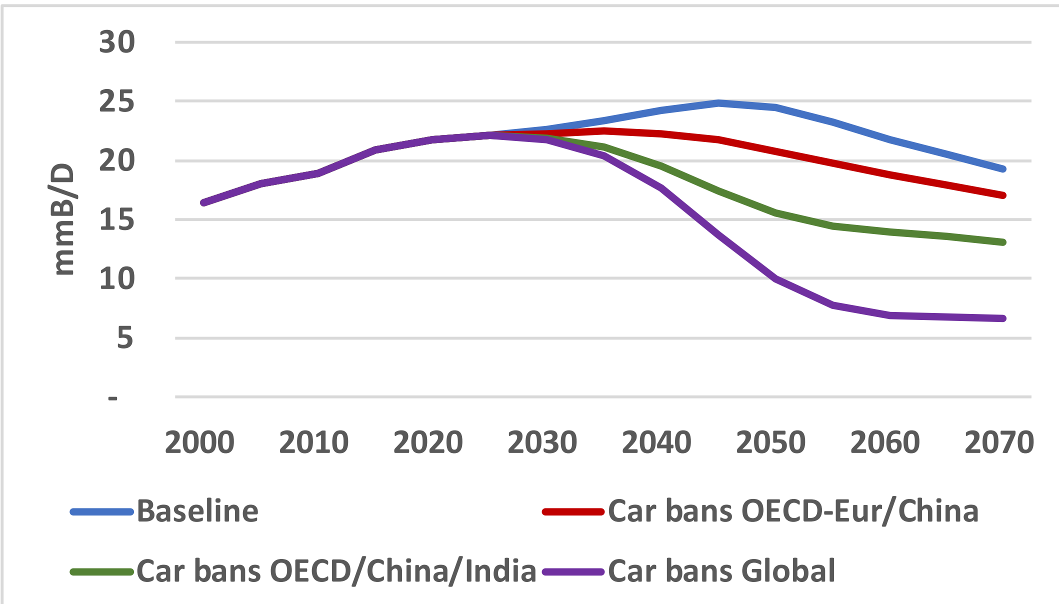


There are policies that can speed the rate of stock turnover, such as the Obama administration's cash for clunkers program. Such policies can retire older vehicles early and incentivize purchases of sustainable new vehicles (Mian and Sufi, 2012). However, one study indicates that incentivized retirement policies can be expensive and eliminate vehicles that might have been retired anyway within a few years (Dews, 2013). Such programs are still popular with policy makers. In the fall of 2019, U.S. Senator Chuck Schumer D-NY unveiled a plan that proposed to offer cash vouchers to Americans with older vehicles of at least eight years old to shift to a new cleaner vehicle such as an electric vehicle, plug-in hybrid, or fuel-call car (Shepardson, 2019).

There are other potential effects of ICE ban policies that are difficult to gauge. For example, electric light duty vehicles have substantially reduced energy and operational costs versus the average ICE, in some cases exhibiting over a 50% reduction in per mile costs (IEA GEVO, 2018). A steep reduction in the cost to drive could result in a rebound effect, where consumers are less motivated to curtail Vkt (vehicle kilometers traveled) due to a dampened price signal. While rebound effects from reduced price signals were not explicitly included in this research, they should be considered as potential subjects for future inquiry.

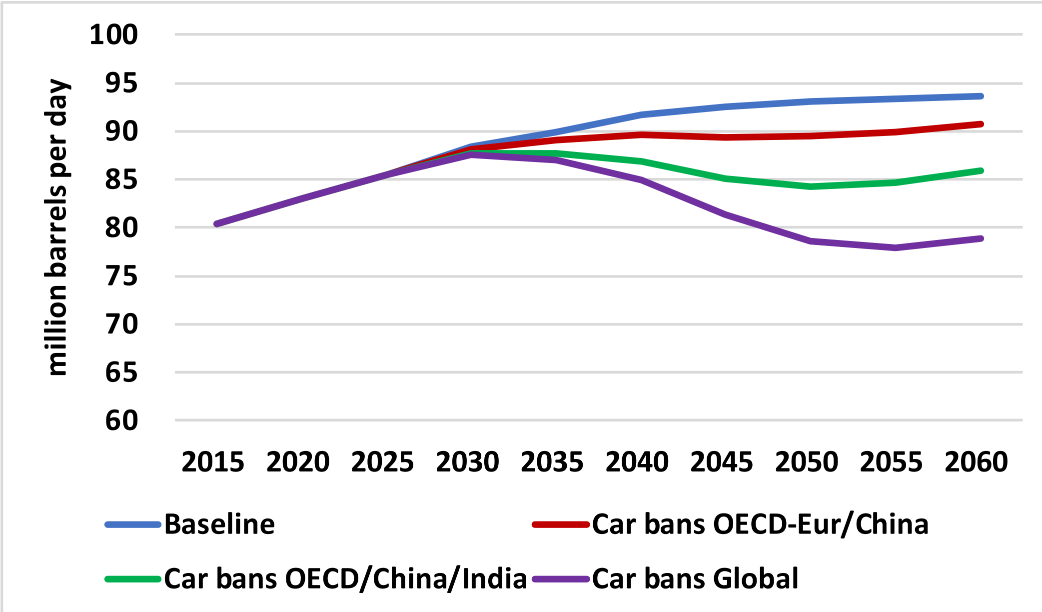
The net effects on LDV oil demand from the various scenarios are shown in Figure 5. The policy begins to save oil around 2030 and achieves significant savings by 2040, given the ramp-up. By 2040, the impact ranges from 2 to 6 million barrels per day depending on the scenario. By 2050 it reaches around 5 million barrels per day in the OECD-Eur/China scenario and nearly 15 million in the global scenario. Oil use levels off in the global ban scenario after 2050, as the remaining PHEVs continue to consume some oil.

Figure 5. ICE Sales Ban Oil Demand Impacts (Oil Use in LDVs Globally)



Applying these reductions in transport oil use, we incorporate our ICE ban scenario results into projections for total global oil demand. Our ICE ban scenarios have a modest impact compared to the baseline reference case where oil demand continues to rise until 2045 and then peaks. As shown in Figure 6, a limited ICE engine ban in OECD-Europe and China in 2040 is sufficient to flatten the rise in total global oil demand and only triggers peak in oil use in the 2040s. Eventually, however, rising population growth undermines this flattening of oil use into the 2050s and beyond. By contrast, our extended scenario including all OECD countries, China and India, quickly produces a peak in global oil demand, beginning around 2035. The global ban scenario also triggers this peak in the 2030-2035 time frame, and causes it to become much more pronounced after 2040, with demand dropping below 2015 levels by 2050.

Figure 6. ICE Engine Ban Scenarios and Global Oil Use

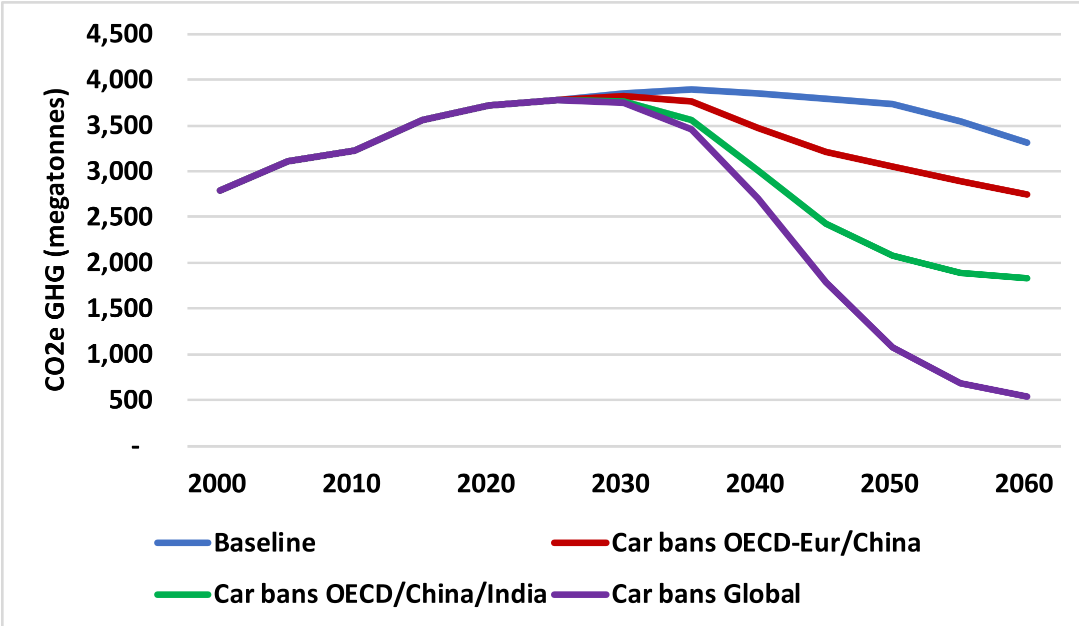


The impacts of the ICE ban scenarios on light-duty vehicle CO2 emissions are significant after 2035 (Figure 7). Even in the Baseline scenario, global LDV CO2 emissions drop from 2040 onward as travel growth is more than offset by efficiency improvements and some shifts to electric vehicles. In the most limited ban scenario covering just OECD Europe and China, CO2 emissions by 2060 drop down to their 2010 level, around 3000 megatonnes. Adding India brings this to 2000 by 2060, and adding the rest of the world results in it reaching around 500 megatonnes, on the order of 80% below 1990 emission levels.

Achieving these very low levels of CO2 is due both to the shifts to electric vehicles (and electricity). Our findings show that if electricity is decarbonized at a rapid rate around the world after 2030, it can seriously accelerate the benefit of shifting to PEVs in line with IEA's ETP 2 Degrees Scenario. In a scenario with slower decarbonization of the electric sector, the change in emissions consequences of ICE engine bans would be more limited, especially in the 2040-2050 time frame.

Our modeling suggests that policies related to ICE engine bans should be made hand to hand with policies reducing the use of carbon intensive fuels in the power generation sector either by substituting for clean energy or by adding carbon capture and sequestration.

Figure 7. LDV CO2e GHG Emissions



4. Conclusion and Policy Implications

We find that several countries and localities are considering ICE sales bans as a means to address air pollution and mitigate rising greenhouse gas emissions, while reducing national reliance on oil products. We utilize a sales/stock/travel scenario spreadsheet tool calibrated to align with the International Energy Agency's bottom-up, transport model MoMo to analyze the impact of national bans on new sales of light-duty ICE passenger cars.

We find the proposed ICE sales bans in Europe and China could eventually reduce about 5.5 mmboe/d of oil use by 2050. Taken alone, this erosion of demand would not have the potential to trigger peak global oil use quickly. A full global ban on ICE engine sales would have a more significant impact on global oil use, eliminating about 15 million b/d of demand after 2050 and creating a permanent peaking and sustained downturn in oil use. Our results imply that the impact of proposed ICE engine sales bans on oil businesses could be a delayed one that still leaves room for both production of legacy assets and even potentially new oil finds, though there will likely be other policies and circumstances that will have additional impacts.

Another implication of these findings is that other, additional complementary policies will be needed to supplement national ICE engine bans for a timely reduction of oil use and related carbon emissions to stabilize climatic change. Limited ICE engine bans in

Europe and China are likely not sufficient to bring global emissions down to levels needed to limit global warming to the 2 degrees Celsius target consistent with the Paris agreement. Moreover, to be most effective, they should be coupled with deep decarbonization of the power generation sector. If coupled with a decarbonized electric grid, a global sales ban on ICE engines could bring carbon emissions from light duty passenger vehicles to zero by 2060.

National ICE engine bans could be easier to implement at scale than closing small urban pedestrian centers to passenger car traffic, but cities can still play a strong role in reducing transport emissions. We recommend that cities look at a wider array of policies to combine with a ban on ICE engines in urban centers in their efforts to reduce carbon emissions including land use changes that encourage use of public transit, walking, and bicycling. Policies aimed to decarbonize the freight sector via alternative fuels and optimization technologies are another promising avenue to complement ICE bans on passenger vehicles.

There are a number of potential subjects for future inquiry. One would be to better understand how quickly cities could transform themselves and rapidly cut car use, based on the fastest historical cases (such as Copenhagen). Another would be to consider how soon a national ICE ban would begin to affect behavior, i.e. if passenger vehicle owners would anticipate the ban and shift their purchases away from ICE engine cars up to a decade in advance of the target date, given the clear commitment. The pace of Europe’s current abandonment of diesel engine vehicles might shed some light on this notion. In Europe, sales of diesel engine cars have plummeted in the past year as Germany and other countries have mooted banning their use in urban settings.

Discussion of bans is currently taking place somewhat haphazardly but could be better integrated into global governance structures of global climate negotiations. In particular, nationally determined individual reduction pledges should include both realistic timelines for an outright or partial ban of ICE engines sales, increased investment for public transport expansion plans, and smart urban design and transit-oriented development to increase accessibility while lowering dependence on individual passenger car use.

References

Annual Vehicle Statistics 2018, Motor Vehicle Population by Vehicle Type https://www.lta.gov.sg/content/dam/ltaweb/corp/PublicationsResearch/files/FactsandFigures/MVP01-1_MVP_by_type.pdf Accessed August 28, 2018.

Boston, W., 2018. VW Maps Plan to Overtake Tesla in Electric Cars. MarketWatch. https://www.marketwatch.com/story/vw-maps-plan-to-overtake-tesla-in-electriccars-2018-03-13

Boston Metropolitan Planning Organization, 2018 Gehrke, S.R., A. Felix, Reardon,T. Fare Choices: A survey of ride-hailing Passengers in Metro Boston. Report 1. MAPC Research Brief https://www.mapc.org/farechoices/ Accessed August 28, 2018.

Brand, C., 2016. "Beyond 'Dieselgate': Implications of unaccounted and future air pollutant emissions and energy use for cars in the United Kingdom," Energy Policy (97) pp 1-12, https://www.sciencedirect.com/science/article/pii/S030142151630341X

Brandt, A., et al, 2013. Peak Oil Demand: The Role of Fuel Efficiency and Alternative Fuels in a Global Oil Production Decline. Environmental Science and Technology, 47 (14) pp. 8031-8041. DOI:101021 es401419t https://pubs.acs.org/doi/full/10.1021/es401419t#citing Accessed August 28, 2018.

Broekhoff, D.; Erickson, P., and Lee, C., 2015. What Cities Do Best: Piecing Together an Efficient Global Climate Governance. Seattle: United States. Stockholm Environment Institute https://www.sei.org/mediamanager/documents/Publications/Climate/SEI-WP-2015-15-Cities-vertical-climate-governance.pdf

Brown, S. P. A., and Huntington, H., 2017. "OPEC and World Oil Security" Energy Policy (108) pp. 512-523, https://www.sciencedirect.com/science/article/pii/S0301421517303889 Accessed September 28, 2018.

BP p.l.c. 2017. BP World Energy Outlook. London: U.K. https://www.bp.com/content/dam/bp/pdf/energy-economics/energy-outlook-2017/bp-energyoutlook-2017.pdf Accessed March 29, 2018.

Campbell P., 2018. "Diesel car sales fall almost 40% as UK buyers hit brakes," Financial Times, https://www.ft.com/content/70131c46-38b6-11e8-8eee-e06bde01c544

Cathkart-Keays, A., 2015. Will we ever get a truly car-free city? The Guardian. https://www.theguardian.com/cities/2015/dec/09/car-free-city-oslo-helsinki-copenhagen. Accessed September 28, 2018.

Dahiya, S.; Myllyvirta, L. and Sivalingam, N., 2017. Airpocalypse: Assessment of Air Pollution in Indian Cities. Bangalore: India. Greenpeace. https://securedstatic.greenpeace.org/india/Global/india/Airpoclypse--Not-just-Delhi--Air-in-most-Indian-cities-hazardous--Greenpeace-report.pdf Accessed August 28, 2018.

Davis, L. W., 2017. Saturday Driving Restrictions Fail to Improve Air Quality in Mexico City. *Sci. Rep.***7**, 41652; doi: 10.1038/srep41652

Davies, A., 2017. General Motors is Going All Electric. WIRED (New York, NY). https://www.wired.com/story/general-motors-electric-cars-plan-gm/ Accessed August 28, 2018.

Dews, F., 2013, "Cash for Clunkers: More Costly, Less Effective," Brookings, https://www.brookings.edu/blog/brookings-now/2013/11/07/cash-for-clunkers-more-costly-less-effective/

Erickson, P. and Tempest, K., 2015. Keeping Cities Green: Avoiding Carbon Lock-in Due to Urban Development. Seattle: United States. Stockholm Environment Institute. https://www.researchgate.net/publication/282706222_Keeping_cities_green_Avoiding_carbon_lock-in_due_to_urban_development Accessed. September 28, 2018.

EU Commission, *Post-2020 CO2 emission performance standards for cars and vans,* Report on the European Parliament and the Council adopted Regulation (EU) 2019/631 setting CO_2 emission performance standards for new passenger cars and for new light commercial vehicles (vans) in the EU for the period after 2020, posted 17 April 2019, https://ec.europa.eu/clima/policies/transport/vehicles/regulation_en

Fagnant, D. and Kockelman, K., 2014. The Travel and Environmental Implications of Shared Autonomous Vehicles, Using Agent-based Model Scenarios, Transportation Research 4D (2014): 1-13. https://ac.els-cdn.com/S0968090X13002581/1-s2.0-S0968090X13002581-main.pdf?_tid=639bd173-e2df-403c-a3a4-4f8e00f190ea&acdnat=1522440986_766244c9c7e864a8b5ee35be41b62674

Ford Motor Company, 2017. "London Trials New Plug-in Hybrid Vans That Could Help to Deliver Cleaner Air; Supports Ford's Push for EV Leadership," Ford Motor Company Website, https://media.ford.com/content/fordmedia/feu/en/news/2017/01/20/london-trials-new-plug-in-hybrid-vans-that-could-help-to-deliver.html

Ford Motor Company, 2019, "Our Future is in Motion: Climate Change Scenario Report," Ford Motor Company Website, https://corporate.ford.com/microsites/sustainability-report-2018-19/assets/files/sr18-climate-change-scenario-2019.pdf

Fulton, L.; Mason, J. and Meroux, D., 2017. The Three Revolutions in Urban Transportation. UC Davis Institute of Transportation Studies. https://steps.ucdavis.edu/three-revolutions-landing-page/ Accessed August 25, 2018.

Fulton, L.; Cazzola, P. and Cuenot, F., 2009 IEA Mobility Model (MoMo) and its use in the ETP. Energy Policy 37 no. 10: 3758–3768. https://doi.org/10.1016/j.enpol.2009.07.065

Garfield, L, 2018. 13 Cities That Are Starting to Ban Cars Business Insider. *Business Insider*. http://www.businessinsider.com/cities-going-car-free-ban-2017-8 Accessed March 12, 2018.

Greenblatt, J., 2015. Autonomous Taxis Could Greatly Reduce Greenhouse-gas Emissions of US Light-duty Vehicles. *Nature Climate Change* 5: 860-863.

Green Car Congress, 2019, https://www.greencarcongress.com/2019/04/20190430-china.html

Haas, P., et al., 2010 Transit Oriented Development and The Potential for VMT-related Greenhouse Gas Emissions Reduction Growth. Center for Transit Oriented Development. http://ctod.org/pdfs/2010TODPotentialGHGEmissionsGrowth.pdf Accessed September 30, 2018.

Hawkins, A.J. and Calma, J. 2019. “Chuck Schumer proposes ‘large discounts’ to trade in gas-powered cars for electric ones” The Verge. https://www.theverge.com/2019/10/25/20931983/schumer-electric-car-trade-in-gas-discount-proposal-zero-emission

Hockenos P., “End of the Road: Are Diesel Cars on the Way Out in Europe?” Yale Environment 360, https://e360.yale.edu/features/end-of-the-road-are-diesel-cars-on-the-way-out-in-europe

ICCT, Prospects for fuel efficiency, electrification and fleet decarbonisation, for Global Fuel Economy Initiative (GFEI), June 2019 https://www.globalfueleconomy.org/data-and-research/publications/gfei-working-paper-20

Innovation Center for Energy and Technology, 2019, “A Study On China’s Timetable For Phasing-Out Traditional Ice-Vehicles,” http://nrdc.cn/Public/uploads/2019-05-24/5ce7931eb51b3.pdf

International Energy Agency. 2017. Energy Technology Perspectives. Paris: France. https://doi.org/10.1787/energy_tech-2017-en Accessed September 28, 2018.

International Energy Agency, 2019, “Global EV Outlook,” https://www.iea.org/gevo2019/ Accessed September 9, 2019.

Jaffe, Amy Myers. 2016. “The Role of the USA in the Geopolitics of Climate Policy and Stranded Oil Reserves” *Nature Energy*, 1: 1-4

Jaffe, Amy Myers. 2019. “The Tech Enabled Energy Future. Council on Foreign Relations. https://www.cfr.org/report/tech-enabled-energy-future

Kodjak, D., et al, 2019. “Prospects for Fuel Efficiency, Electrification and Fleet Decarburization,” Globalfueleconomy.org, https://www.globalfueleconomy.org/media/708302/gfei-working-paper-20.pdf

Land Transport Authority. 2017. Government of Singapore https://www.lta.gov.sg/apps/news/page.aspx?c=2&id=b010406e-6edf-4224-9cd1-928706cd6fe7 Accessed August 28, 2018.

Levenson H.S, et al 2003. Bus Rapid Transit: Synthesis of Case Studies. Transportation Research Record. http://trrjournalonline.trb.org/doi/abs/10.3141/1841-01 Accessed September 28, 2018.

Litman, T., 2018. “Land Use Impacts on Transport” Victoria Policy Institute, http://www.vtpi.org/landtravel.pdf Accessed September 30, 2018.

Majors, J. 2015. “Assessment of the Impact of the Indianapolis Cultural Trail: A Legacy of Gene and Marilyn Glick. http://indyculturaltrail.org.s3.amazonaws.com/wp-content/uploads/2015/07/15-C02-CulturalTrail-Assessment.pdf Accessed February 2, 2018.

Mason, J. Fulton L., and McDonald, Z., 2015. A Global High Shift Cycling Scenario. Institute for Transportation & Development Policy available at https://3gozaa3xxbpb499ejp30lxc8-wpengine.netdna-ssl.com/wp-content/uploads/2015/11/A-Global-High-Shift-Cycling-Scenario_Nov-2015.pdf Accessed September 30, 2018.

Mayor of London. 2017. Travel in London. Report 10. http://content.tfl.gov.uk/travel-in-london-report-10.pdf Accessed September 28, 2018

McKinsey & Co. 2016. Sharma, N., Sutorius, r. et al, https://www.mckinsey.com/industries/oil-and-gas/our-insights/is-peak-oil-demand-in-sight Also presentation materials available at https://its.ucdavis.edu/2017-asilomar-biennial-conference-summary/ Accessed September 28, 2018.

Meszler, D., German, J. et al, 2016. “CO2 Reduction Technologies for the European Car Fleet a 2025-2030 Assessment.” ICCT White Paper, International Council on Clean Transportation Europe. https://www.theicct.org/publications/co2-reduction-technologies-european-car-and-van-fleet-2025-2030-assessment Accessed September 28, 2018

Atif Mian and Amir Sufi, 2012 “The Effects of Fiscal Stimulus: Evidence from the 2009 Cash for Clunkers Program,” The Quarterly Journal of Economics, https://academic.oup.com/qje/article-abstract/127/3/1107/1924374

Newman, P., Beatley T., and Boyer, H., 2009 Resilient Cities: Responding to Peak Oil and Climate Change. Island Press. Washington D.C.

New York City Department of Transportation. 2013. The Economic Benefit of Sustainable Streets. http://www.nyc.gov/html/dot/downloads/pdf/doteconomic-benefits-of-sustainable-streets.pdf Accessed February 2, 2018.

Nieuwenhuijsen, M. and Khreis, H. 2016. “Car-free Cities: Pathway to Healthy Urban Living,” Environment International 94: 251–262. https://doi.org/10.1016/j.envint.2016.05.032

Nieuwenhuijsen, M. et al. 2014. “Positive health effects of the natural outdoor environment in typical populations in different regions in Europe (PHENOTYPE): a study programme protocol,” *BMJ Open*, 4. https://doi.org/10.1136/bmjopen-2014-004951

Oregon Department of Transportation. 2016. Portland Region 2016 Traffic Performance Report. Region 1. https://www.oregon.gov/ODOT/Regions/Documents/Region1/2016_TPR_FinalReport.pdf Accessed September 28, 2018.

O’Shaughnessy, E. et al, 2016. “Estimating the National Carbon Abatement Potential of City Policies: A Data Driven Approach”. Technical Report NREL/TP-6A20-67101. 10. https://www.nrel.gov/docs/fy17osti/67101.pdf Accessed August 28, 2018.

Pham, S., 2017. “Volvo: Gas-only cars are history after 2019,” CNN Money (Hong Kong, People's Republic of China). http://money.cnn.com/2017/07/05/autos/volvo-electric-cars-internal-combustionengine/index.html?iid=EL Accessed February 6, 2018.

Plotz P, et al, 2019. “Designing car bans for sustainable transport,” Nature Sustainability, 2, 534-536

Rayle, L. el al, 2014. App-Based, On-Demand Ride Services: Comparing Taxi and Ridesourcing Trips and User Characteristics in San Francisco. San Francisco: United

States. University of California Transportation Center.
https://www.its.dot.gov/itspac/dec2014/ridesourcingwhitepaper_nov2014.pdf
Accessed February 6, 2018.

Ramaswami, A. et al 2012. "Quantifying Carbon Mitigation Wedges in U.S. Cities Near-Term Strategy Analysis and Critical Review," Environmental Science & Technology 46, no. 7: 3629−3642. https://doi.org/10.1021/es203503a

Reuters, 2015. "Oslo Aims to Make City Center Car-free within Four Years," https://www.reuters.com/article/us-norway-environment-oslo/oslo-aims-to-make-citycenter-car-free-within-four-years-idUSKCN0SD1GI20151019
Accessed September 28, 2018.

Rode, P. et al, 2014. "Accessibility in Cities: Transport and Urban Form," NCE Cities – Paper 03. London: U.K. London School of Economics.
https://files.lsecities.net/files/2014/11/LSE-Cities-2014-Transport-and-Urban-Form-NCECities-Paper-03.pdf Accessed August 28, 2018.

Rose, Jonathan, F.P., (2016) *The Well Tempered City.* Harper Collins. New York: New York.

Rose, Eliot and Rex Burkholder. 2009. "CO2 Reduction Through Better Urban Design" Daniel Sperling and James. S. Cannon (eds) Reducing Climate Impacts in the Transport Sector. Springer, Switzerland. 139-158

Salon, D. 2012 "How do local actors affect VMT: A critical view of the empirical evidence. Transportation Research Part D. Transport and Environment 17 (7) 495-508 https://www.sciencedirect.com/science/article/pii/S136192091200051X?via%3Dihub
Accessed August 28, 2018.

Sayare, S. 2014. "Fighting Pollution, Paris Imposes Partial Driving Ban. The New York Times. https://www.nytimes.com/2014/03/18/world/europe/fighting-pollution-paris-imposes-partial-driving-ban.html Accessed September 28, 2018.

Schipper, L. and C. Marie-Lilliu. 1999. "Transportation and CO_2 Emissions: Flexing the Link A Path for the World Bank," Environmental Department Papers - Paper No. 69. Paris: France. International Energy Agency
http://documents.worldbank.org/curated/en/826921468766156728/Transportation-and-CO2-emissions-flexing-the-link-a-path-for-the-World-Banlk
Accessed February 5, 2018.

Shepardson, David. 2019. Senate Democrat Schumer proposes plan to swap gas cars for electric vehicles, Reuters, https://www.reuters.com/article/us-autos-emissions-congress/senate-democrat-schumer-proposes-plan-to-swap-gas-cars-for-electric-vehicles-idUSKBN1X403N Accessed October 25, 2019.

Spitzer D. 2018, "ICE-Free Cities: Global Strategies for Creating Sustainable Urban Transport," Natural Resources & Environment; Chicago Vol. 33, Iss. 2, (Fall 2018): 8-11.

Ter-Minassian, T., 2017. "Promoting effective and fiscally sound local investments in infrastructure" (Brookings Institution, 2017) https://www.brookings.edu/wp-content/uploads/2017/09/cs_20170911_investments_in_infrastructure.pdf Accessed September 28, 2018.

Tønnesen, A. et al. 2016. Europeiske Byer Med Bilfrie Sentrum. Oslo: Norway. Transportøkonomisk Institutt. https://www.toi.no/getfile.php?mmfileid=42371 Accessed August 28, 2018.

U.S. Energy Information Administration. Jan. 2018. Monthly Energy Review. Washington, D.C.: United States. https://www.eia.gov/totalenergy/data/monthly/ Accessed February 2, 2018.

U.S. Environmental Protection Agency. 2017. Fast Facts on Transportation Greenhouse Gas Emissions. Washington, D.C., United States. Jul. 2017. https://www.epa.gov/greenvehicles/fast-facts-transportation-greenhouse-gas-emissions Accessed February 2, 2018.

World Economic Outlook Database. International Monetary Fund. Washington, D.C.: United States. Continually updated. https://www.imf.org/external/pubs/ft/weo/2017/01/weodata/index.aspx Accessed March 3, 2018.

U.S. Government Accounting Office. 2014. Public Transportation: Multiple Factors Influence Extent of Transit Oriented Development GAO-15-70. Washington D.C., United States, November 2014. https://www.gao.gov/assets/670/666992.pdf Accessed September 30, 2018.

Wright, L. 2005. Sustainable Transport: A Sourcebook for Policy-makers in Developing Cities Module 3e Car-Free Development. Eschborn: Germany. Deutsche Gesellschaft für Technische Zusammenarbeit.

Acknowledgements

Authors would like to thank Stefan Koester for his research and editing contributions for this article. We also thank the Alfred P. Sloan Foundation for its support to the Council on Foreign Relations for study of the impact of technologies on global energy markets.